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THE MECHANICAL EQUIVALENT OF LIGHT.

By Herbert E. Ives, W. W. Coblentz and E. F. Kingsbury.

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Introduction.

THE mechanical equivalent of light has been the subject of investigation by Tumlirz,[1] Angstrom[2] and others. Knowing as we do that

[1] Annalen der Physik, 38, p. 650, 1889.

[2] Annalen der Physik, 67, p. 648, 1899.

objective light and radiant energy are one and the same thing, it is but natural that attempts should be made to obtain the one in terms of the absolute units in which the other is specifiable. These early measurements, with which the term "mechanical equivalent of light" has been associated, were most unfortunately based upon a hazy and immature idea of what constitutes "light." Under this condemnation must fall as well numerous determinations of "luminous efficiency," for the two quantities are of necessity closely interrelated. In brief, light has been considered merely as radiation that can be seen, quite irrespective of the widely different capacities of the various "visible" radiations to excite the subjective sensation of light. As a consequence the physically determined "luminous efficiencies" and "mechanical equivalents" (this latter different for every light source) have no definite relationship to the "efficiencies" and "specific consumptions" used by the engineer. These latter are rational and consistent quantities (which the physical ones are not), though unfortunately related to the chance dimensions of the first measured candle instead of to the C.G.S. units. The present investigation was undertaken to establish on a consistent scheme, in terms of the fundamental physical units, the real values of the light units now in practical use.

The relationship between light and power upon which this work is based are developed in a paper by one of the present writers under the title: "The Primary Standard of Light,"[1] to which reference may be made by those unfamiliar with the subject. In that paper it is proposed that light be defined as radiant energy flux evaluated according to its capacity to produce the sensation of light. It is further proposed that the standard of luminous flux be one watt of radiation of maximum luminous efficiency. More mature thought on the subject suggests, however, that this statement of the proposed standard is more complicated than need be. Accepting the definition of light there given, it is quite sufficient to say that *the unit of luminous flux shall be the watt.* The determination of the mechanical equivalent of light, therefore, becomes merely the fixing of the lumen in terms of the watt.

2. Definitions of Light and Luminous Quantities.

The discussion of this subject can be much shortened by adopting at the start a set of definitions of the quantities frequently entering in. These are taken partly from those now in technical use, and partly either taken or adapted from a list suggested by Ives.[2]

[1] Ives, Astrophysical Journal, XXXVI., No. 4, Nov., 1912, p. 322.

[2] Lighting Journal, Vol. 1, Oct., 1913, p. 250.

Power consumed by a light source = P; expressed in watts, a portion of which is dissipated by radiation, the remainder by conduction and convection.

Power radiated by a source = $R = \int_0^\infty R_\lambda d\lambda$ = power emitted by a light source in the form of radiation between wave-lengths 0 and ∞, expressed in watts.

Radiation efficiency = R/P = ratio of the power dissipated as radiation to the total amount of power consumed by the source (a pure numeric).

Luminous flux = F = radiant power evaluated according to its capacity to produce the sensation of light.

Light evaluating factor or stimulus coefficient of any radiation is the ratio of the luminous flux, in its appropriate units, to the radiant power producing it, in its appropriate units.

The luminous efficiency of any radiation = L_R, = the relative capacity of the radiation to produce the sensation of light, compared with the capacity of the same quantity of radiation of the maximum possible light producing capacity (a pure numeric).

The total luminous efficiency of a light source = L_r = the relative capacity of the power applied to a light source to produce the sensation of light, compared with the capacity of the same quantity of power in the form of radiation of maximum possible luminous efficiency (a pure numeric).

Units.—Luminous flux is connected to radiant power by a numerical evaluating factor. The unit of power is the watt. The present arbitrary practical unit of luminous flux is the lumen. The light evaluating factor or stimulus coefficient is consequently expressed in lumens per watt. If for this evaluating factor is taken the *luminous efficiency* as above defined, the unit of luminous flux is the same as that of radiant power or applied power, namely the *watt.*

In order to go over to the watt as the unit of luminous flux it is necessary to know the:

Mechanical Equivalent of Light = the value of the lumen in watts of luminous flux.

The simplicity of these relationships is illustrated by the equation,

Power consumed × radiation efficiency × radiant luminous efficiency = luminous flux,

in which every quantity of interest in the study of an illuminant finds its place.

This simplification is only possible if there does exist a definite prac-

tically establishable "radiant luminous efficiency." Put another way this means that there must exist a definite luminosity curve of the spectrum. While this latter is actually a function of intensity, size of the field of view, etc., reasons have been given elsewhere[1] for believing that the practical situation is adequately met by the adoption of a high intensity luminosity curve as determined by a certain set of photometric conditions. For this will be used the luminosity curve of the normal equal energy spectrum as determined by Ives as the mean of 18 observers and the same curve as determined by Nutting[2] as the mean of 21 observers. As will be seen, the present investigation offers a means of deciding between these slightly different curves.

3. Methods for Determining the Mechanical Equivalent.

In general the determination of the mechanical equivalent of light consists in the measurement of the same luminous flux in both watts and lumens, from which measurement the ratio of the two can at once be determined.

It usually happens, however, that the radiation is not presented to the energy measuring instrument already evaluated as "light," consequently this value must be deduced from the value of the total radiation and its radiant luminous efficiency. It may happen too that the value of the radiation must be deduced from the total input through a known or probable value of the radiation efficiency. According as one or other of these contingencies is met we find three fairly distinct experimental methods of approaching the problem, as follows:

A. Through the graphical evaluation as light of a known energy distribution.

This may be illustrated by calculations on a black body. Thus Nernst[3] has measured the brightness of a black body (solid angular luminous flux density per unit area); the radiation constant (solid angular radiation flux density per unit area) has been the subject of numerous measurements,[4] and the distribution of energy through the spectrum may be calculated from the Wien-Planck equation. Now, by multiplying the latter by the radiant luminous efficiency or luminosity curve of the spectrum, of maximum value unity, a "reduced" area is obtained, the ratio of which to the total area is the radiant luminous efficiency. We then have

[1] Ives, "Studies in the Photometry of Lights of Different Colors," Phil. Mag., July, Sept., Nov., Dec., 1912.

[2] Trans. Illuminating Eng. Soc., Vol. IX., No. 7, p. 633, 1914.

[3] Physikal. Zeit., Vol. 7, p. 380, 1906.

[4] See Coblentz, Bureau of Standards Bulletin, 11, p. 87, 1914.

radiated power × radiant luminous efficiency = *luminous flux in ergs per second or in watts*, and (from the candle power measurements) *luminous flux in lumens*,

from which the ratio of the lumen to the watt may be obtained.

A similar case is that presented by the incandescent electric lamp, in which we know the power input, the efficiency losses (approximately), the luminous output in lumens, and the radiant luminous efficiency from energy distribution curves and the luminosity curve of the eye.

Values calculated by this method have been published by Ives and others.[1] Reducing them to what they would be if the luminosity curves here adopted were used, the lumen is found to be about 1/800th of the watt. The defect of this method is that the luminous portion of the spectrum, upon which the evaluating process must be carried out, is an excessively small part of the whole, in which experimental errors of determination or deficiencies in the theoretical formula for energy distribution figure disproportionately.

B. Through mechanical evaluation of a given radiant energy flux as light, by the use of absorbing media or equivalent means.

This method does mechanically what the previous method does indirectly by calculation. Imagine an absorbing screen whose transmission is exactly according to the normal equal energy spectrum luminosity curve of the eye, with a maximum transmission of unity. Measure in absolute units the radiation transmitted through it. Measure also the luminous flux from the same light source in lumens. The figures obtained give the ratio desired.

This method is quite the simplest and most direct, once the spectrum luminosity curve is established and the ideal absorbing medium is at hand. It is the method suggested by Houstoun.[2] Another variation of the same idea is the suggestion of Strache,[3] to form a spectrum, pass it through an opening cut to the shape of the visual luminosity curve, and then measure the radiation in absolute units. No determinations made by this method have been published.

C. The measurement of a selected monochromatic radiation, of known luminious efficiency, as light and power.

This method, which in principle differs in no way from the others, has some advantages. For instance the value obtained for the luminous equivalent of the monochromatic radiation has an independent value in that it can be used with any luminosity curve, not only with the one selected by the experimenter. If the monochromatic radiation is

[1] Electrical World, June 15, 1911, p. 1565.

[2] Proc. Royal Soc., A, 85, 275, 1911.

[3] Proc. American Gas Institute, 2, 401, 1911.

selected near the maximum of visual sensibility the resultant value is largely independent of errors in the determination of the ends of the luminosity curve, since the maximum is fairly well agreed upon.

The great difficulty in the determination by this method is the measurement of the colored light, for which special methods are necessary. By the other methods the colored-light photometry is performed entirely in the determination of the luminosity curve, since the light source measured can always be of the color of the standard.

All the published experimental determinations have been made by this last method. Drysdale,[1] using the spectrally resolved light of the carbon arc, obtained for yellow-green light 210 lumens per watt. Nutting,[2] by a similar procedure obtained 170 lumens per watt for wavelength .566 μ. Buisson and Fabry,[3] measuring the monochromatic green mercury radiation found the value 690. The first two values are unquestionably much too low, probably due on the one hand to scattered radiation, and on the other to the crudity of the methods of measuring the intensity of the colored light. Fabry's value is of the order of magnitude of the calculated figure, but was confessedly weak on the photometric end. The green light was evaluated by simple direct comparison, several observers being used. Their energy standard was probably in error to some extent (see reference 9), but their value is nevertheless remarkably close to the one here obtained.

4. Apparatus and Methods of the Present Investigation.

The aim in the present work has been: first, to develop methods of attack in which the highest attainable accuracy, both photometric and radiometric, may be obtained, and, second, to establish the value of the lumen in terms of the watt with a degree of accuracy sufficient to make that ratio of immediate use in the technology of light production and utilization.

Both experimental methods above outlined (*B* and *C*) were used. A description of the apparatus and method of use follows:

(*a*) *Method B.*—The most important factor in method *B* is the absorbing medium whose transmission shall be the luminosity curve of the normal energy spectrum. The ideal screen would be one whose maximum of transmission was unity and which absolutely matched the curve in question. But neither of these conditions is absolutely necessary. Any other maximum transmission than unity merely involves the correc-

[1] Proc. Royal Soc., 80, 19, 1907.

[2] Electrical World, June 26, 1908.

[3] Compt. Rend., 153, 254, 1911.

tion of the value found for the transmitted energy to what it would be were the value unity. If the transmission is not exactly in accordance with the ideal curve it is possible by graphical calculation to determine with considerable accuracy the correction factor to be applied. For this it is only necessary to know the *shape* of the energy distribution in the visible region, not its value relative to the rest of the emission spectrum as in the case of method *A*.

The screen used in this investigation was a solution of certain inorganic salts contained in a parallel-walled glass tank one centimeter in thickness. The composition of this solution is:

Cupric chloride	60.0 g.
Potassium chromate	1.7 g.
Cobalt ammonium sulphate	7.5 g.
Nitric acid, sp. gr. 1.05	15.0 c.c.
Water to	one liter of solution.

The transmission of this solution through the spectrum was measured against that of clear water by means of the sunlight spectro-radiometer described elsewhere.[1] The two tanks were constructed and manipulated as in the previous investigation with photometric absorbing solution described by us.[2] The values obtained are shown in Fig. 1, Curve *a*; in Curve *b* (circles) they are multiplied by the factor 1.3 and compared with the Curve *c*, which is the Ives luminosity curve it is desired to copy. It is evident that the copy of the Ives curve is quite close.

What we are the most interested in is the correction to be applied in the use of this screen under the conditions of the experiment. This is obtained by multiplying the energy distribution curve of the light source employed, at each wave-length by the value of the ideal curve and by the value of the solution transmission. The correction factor is given by the ratio of the areas of the two resulting curves. This process is gone through in Curves *d* and *e*. The energy distribution of the "4-watt" carbon lamp used as light source is taken as being substantially that of a black body at 2,080 degrees absolute, which is calculated from the Wien equation. The ratio of the areas *d* (ideal curve) to *e* (actual curve) is 1.30, which is the factor by which the observed power must be multiplied to obtain the working value, if the Ives curve is used.

The remaining curves of Fig. 1, namely, *f* and *g*, are the luminosity curves as recently determined by Nutting, and the same applied to the "4-watt" lamp. These are included for the reason that the experimental values to be reported upon can be used equally well to determine the mechanical equivalent on the basis of this luminosity curve, which

[1] Description to be published shortly.

[2] Ives & Kingsbury, Trans. Illuminating Eng. Soc., IX., No. 8, p. 795, 1914.

is slightly different from that of Ives, and can in fact be used to decide between the two, in a manner that will be brought out presently. Nutting's curve, determined in substantially the same way as the older one, differs from it chiefly in approaching its maximum more steeply on each side, by reason of which its area is less. In the case of the "4-watt" lamp this difference of area amounts to eight per cent., so that the correction factor becomes $.92 \times 1.30 = 1.1975$. This difference is perhaps

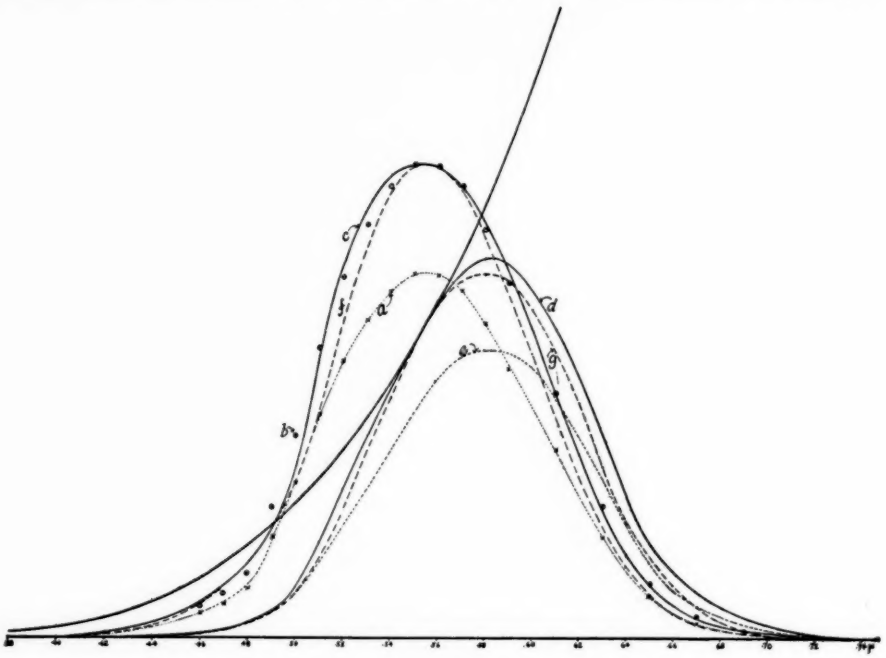

Fig. 1.

Graphical Evaluation of Luminous Flux from "4-watt" Lamp.

due to the characteristics of the two groups of observers, although it has more the appearance of being due to some instrumental difference. Nutting measured the energy distribution of his source at the slit of his observing telescope directly, while Ives had to get his indirectly. While the direct procedure is preferable it may be rendered less accurate by the presence of scattered radiation, apt to be particularly dangerous in the visible spectrum with its small share of the total energy. The Nutting curve agrees, in its shape near the maximum, with the curve determined by Thürmel[1] and others with the Lummer-Pringsheim spectral flicker photometer. As will be shown the agreement or disagreement of methods *B* and *C* furnishes a clue as to which curve is the more likely.

[1] Annalen der Physik, XXXIII., p. 1154, 1910.

The apparatus used for method *B* was a portion of the much more complicated arrangement necessary for method *C*, which is shown in Fig. 2. *G* is the surface thermopile, to be described below, turned to face the radiation standard *R* and the light source *P*. The latter was a "point source" 100 candle-power carbon lamp, set to standard "4-watt" color by comparison with a specially furnished standard from the Bureau of Standards. This was carefully measured for candle-power, through a tank of clear water, in terms of two master standards, also from the Bureau of Standards. Since the transmission of the luminosity curve

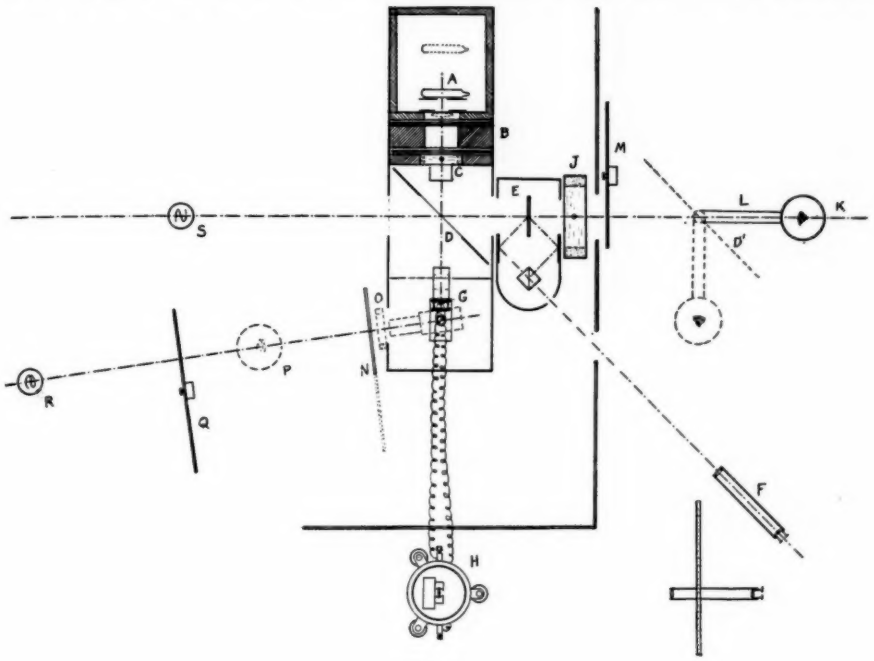

Fig. 2.

Arrangement of Apparatus.

solution was also measured in terms of clear water, the final result is entirely independent of any possible peculiarities of our pair of matched tanks. The luminosity curve solution is shown in position at *O*. At *N* is a shutter, operated from the observing telescope *F*. *Q* is a sector disc, used to reduce the intensity of radiation from the radiation standard, in order to keep all the galvanometer deflections of the same order of magnitude.

The procedure is first to obtain the sensibility of the thermopile by a set of readings on the radiation standard (the lamp *P* and the solution *O* being of course removed): then with lamp and solution in place, to

measure the luminous flux. The candle-power of the lamp, divided by the square of the equivalent air distance (allowing for the absorption of the thermopile window if used), gives the lumens per unit area. The watts per unit area are obtained from the thermopile reading corrected by the ratio already obtained from the measurement of the solution transmission. The ratio of the lumen to the watt can then be immediately derived.

(*b*) *Method C.*—The apparatus for this method is substantially that outlined by Ives in his original suggestion for the watt as the unit of luminous flux.[1] The principal improvement is in the means employed to obtain the photometric value of the green light, which is now made a separate determination, by taking advantage of the researches on colored light photometry and photometric absorbing solutions carried out since the original suggestion was made.

In Fig. 2, *A* is a quartz mercury arc (Heræus 110 volt), *B* is a shutter, operated from a distance, consisting of two parallel sheets of heavy brass, separated by a block of wood, and pierced with round holes with beveled edges. The two elements of the shutter move up and down "straddling" a heavy block of wood having a central opening in line with the axis of the apparatus. At *C* is a glass-walled cell containing a solution of cupric chloride, potassium dichromate and neodymium-ammonium-nitrate, with a little nitric acid. This solution, which was made up empirically, transmits nothing from the mercury arc except the green line .5461 μ, as shown by spectrophotographic and spectroradiometric tests.

At *D* is a transparent mirror of clear white glass. Its function is to reflect a small fraction of the radiation to the Lummer-Brodhun photometer head *E*, while the greater part of the radiation falls directly on the thermopile *G*, which latter is connected with the galvanometer *H*. The thermopile is mounted so that it can be rotated about a vertical axis, the mount being adjustable as to its position in the horizontal plane, while the thermopile can be raised or lowered. By means of these adjustments the pile can be set exactly in the axis of the system and at any desired distance from the arc. The method of performing these adjustments is given shortly.

When the thermopile is turned to one adjustable stop it faces the mercury arc, when turned to the other it faces the radiation standard *R*, which is set accurately at a distance of two meters from the opening of the thermopile, and the shutter *N*, operated from *F*. At *S* is an incandescent lamp candle-power standard. At *K* is a "point source" carbon lamp of the type previously described. *M* and *Q* are sector discs to be

[1] Energy Standards of Luminous Efficiency, Trans. Illum. Eng. Soc., April, 1911, p. 258.

used when desired. The photometer field is read by means of the telescope F which is at such a distance from the thermopile that the body of the observer never comes near it. The whole apparatus is most elaborately protected by a large system of metal and cardboard screens not shown in the schematic figure. By these screens all stray light and radiation are completely excluded.

The various incandescent lamp, standard and comparison, are held constant by voltage readings, on a carefully checked laboratory standard voltmeter connected with the lamps by separate voltage leads carried directly to the sockets. The controlling resistances are all at some distance, so that the heat liberated by them shall have the minimum effect on the thermopile. The mercury arc is connected with an ammeter, but as was anticipated when the transparent mirror scheme was adopted for securing simultaneous photo and radiometric observations, the green radiation cannot be held constant within a hundred per cent. by holding a constant current. Immediately after turning on, the green radiation is only a small fraction of what it becomes after several hours' operation, the current being the same.

From the photometric side the most important part of the apparatus is the glass cell J. This is one of a pair, one containing clear water, the other a green solution which transforms the light from lamp K to an exact subjective match with the monochromatic green mercury radiation. The composition and the experimental determination of the transmission of this solution have already been described in this journal. It is, therefore, sufficient here to state that by its use the actual photometry of the green light is performed in this present experiment by comparison of lights of the same color, while the evaluation of the green light in lumens is given in terms of the mean value obtained by the 61 observers who measured the solution by the photometric method recommended in the previous investigations quoted.[1] It is not believed that the use of more than 61 observers, taken at random, would have altered the value obtained by one per cent.

Essential parts of the apparatus are the means for putting all parts in optical alignment and for determining the various constants. The mercury arc is furnished with a diaphragm about two centimeters wide, which is considerably smaller than the rest of the diaphragming system at B and C. In the center of this diaphragm horizontally is a wire cut off so that its point is in the vertical center. In adjusting the position of the thermopile the mercury arc is moved back to the position shown dotted; a lens, also shown dotted, is inserted, which throws an image of

[1] Ives, Astrophysical Journal, XXXVI., No. 4, Nov., 1912, p. 322; "Studies in the Photometry of Light of Different Colors," Phil. Mag., July, Sept., Nov., Dec., 1912.

the wire point on the photometer screen and on the thermopile mount (or preferably on a ground glass-screen placed in the thermopile mount). The thermopile and photometer head are in the same optical line when this image falls on the center of each. The lens is then removed and the mercury arc so placed that it is seen exactly in the line of the sighting crosslines provided in the photometer head. The thermopile mount is supplied with sighting crosshairs as well, and by their aid the thermopile is properly pointed. When these two adjustments are made the pile is correctly placed except for distance. To set it at the same distance as the photometer screen from the arc, recourse is made to a parallax adjustment. The eye is placed at S, where the diaphragm over the thermopile and the photometer screen (half drawn out to furnish an edge) are seen superposed. On moving the eye up and down, the two objects separate unless they are in the same plane. This adjustment, provided the mirror D is plane parallel, is quite delicate.

The details of these adjustments have been given at some length because the accuracy of the result is directly dependent on their perfection. In some of the preliminary work attempts were made to increase the amount of energy available by concentrating the mercury light with a lens. It was found that it was almost impossible to line up the apparatus twice alike, as shown by the different values obtained for the ratio of illumination to galvanometer deflection. These troubles entirely disappeared with the apparatus as now described.

Before describing the measurement of the various instrument constants it is advisable to describe the procedure in making a measurement. This may be divided into three parts, as follows:

1. The determination of the sensibility of the thermopile.

This is done by turning the thermopile to face the radiation standard, whose radiation is cut down to some convenient value by the disc Q.

2. The simultaneous measurement of the green radiation with the photometer and the thermopile.

This is done with the thermopile turned to face the arc, and with the green solution J in place. When the shutter B is opened one observer notes the galvanometer deflection, the other moves the comparison lamp K until, looking through the telescope F, a photometric match is made. The position of K and the corresponding galvanometer deflection are recorded.

3. The evaluation of the comparison lamp.

This is done by replacing the solution J by the clear water, turning on the candle-power standard S, placed at some convenient point, and making a photometric setting by the movement of K, the light from which

is cut down by the sector disc M. In making this measurement there is again no color difference, and as well, the substitution method is used, eliminating the necessity for reversing the photometer head.

The complete formula used to reduce these observations is as follows:

$$\text{Lumens per watt} = \left(\frac{1}{\mu}\right)\left(\frac{T_R}{R_R}\right)\left(\frac{P_S T_R' T_S T_{TL}}{S_B}\right)\left(\frac{D_{C_1}}{D_S}\right)^2\left(\frac{\theta}{D_C^2 \times \Delta \times W}\right),$$

where

μ = luminous efficiency of the green radiation.
T_R = transmission of reflector D for green light.
R_R = reflecting power of reflector D for green light.
P_S = candle-power of standard S.
T_R' = transmission of reflector D for "white" light.
T_S = transmission of green solution J.
T_{TL} = transmission of glass thermopile window for green light.
D_{C_1} = air distance at which the comparison lamp K gives the same illumination through the clear water tank as the standard lamp S does through the reflector D when placed at the distance D.
θ = temperature coefficient of transmission of green solution J.
S_B = transmission of sector disc M.
D_C = air distance at which comparison lamp K is set when a photometric match is made through the green solution.
Δ = galvanometer deflection, when thermopile is exposed to green radiation.
W = watts per square meter per centimeter deflection.

The last quantity (W) is obtained from the formula:

$$w = \frac{R \times S_A \times T_{TR}}{\delta},$$

where

R = watts per square meter received from the raditaion standard.
T_{TR} = transmission of thermopile window to radiation from standard.
S_A = transmission of sector disc Q.
δ = deflection of galvanometer when thermopile is exposed to standard.

The measurement of these various constants formed one of the most exacting parts of the investigation. The only measurements of unusual character were those on the reflector D. In order to measure its reflection and transmission, arrangements were made by which it could be moved to the position D', and the lamp K was so mounted that it could

be turned about an axis in line with the center of the mirror, as shown by the dotted lines. Needless to say, the greatest care was taken to thoroughly clean the reflector and maintain it clean during both its measurement and its use. The measurements of transmission, reflection, etc., were all made several times, since the accuracy of the result is directly dependent upon the accuracy of these.

The values of the constants as determined and used, are as follows: $\mu = .995$ (value from Ives luminosity curve); $\mu = .985$ (value from Nutting luminosity curve); $T_R/R_R = 1/.1083$; $P_S = 10.0$; $T_R = .895$; $T_S = .0437$; $S_A = .2098$; $S_B = .05285$; $T_{TL} = .91$; $T_{TR} = .777$; $R = .88$ watt per square meter.

Using these values the working formula becomes:

$$\text{Lumens per watt} = \frac{62.2}{\mu} \times \left(\frac{D_{C_1}}{D_S}\right)^2 \times \left(\frac{\theta}{D_C^2 \times \Delta \times w}\right).$$

(*c*) *The Measurement of Radiant Power in Absolute Units.* The Thermopile and Auxiliary Galvanometer.—The thermopile used in making the radiometric measurements was of the surface type, having an area of 12 to 17 sq. mm. This area was somewhat reduced by a diaphragm placed in front of the receivers on the glass window which was used in the actual measurements. This diaphragm was of such size that its aperture was always completely filled by the thermojunction surface. The various distances were measured to it, instead of to the receiving surface four or five millimeters behind, which would have been difficult to locate in the parallax distance adjustment. The thermopile consisted of four units joined in series, with a total resistance of about 31.6 ohms.

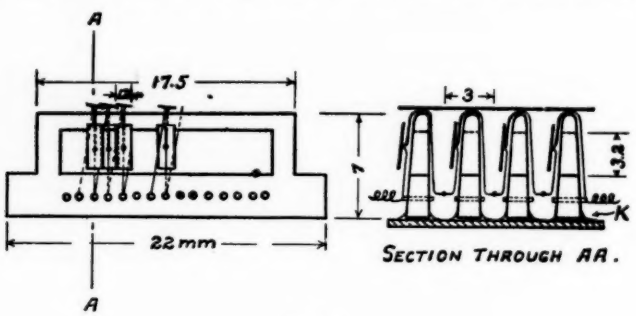

Fig. 3.

Details of Thermopile.

Each unit consisted of 15 thermocouples joined in series as shown in Fig. 3. The receivers were of tin, 1.2 × 3 mm. in area. The thermopile was completely compensated by having receivers upon the unexposed junc-

tions, which were freely suspended in the air, thus admitting a rapid equalization of the temperature, as described elsewhere.[1] By this means drift of the zero reading is reduced to a minimum.

The pile was constructed so that the elements could be joined all (60) in series, or they could be joined one-half (30) in series parallel. When joined all in series the voltage was doubled and the deflections were considerably increased when used with the d'Arsonval galvanometer. When used with a Thomson galvanometer the most efficient combination was the one in which all four units (15 thermocouples in each) were joined in parallel. These incidental details are included here for the completeness of record.[2] The time required to produce a maximum effect upon this thermopile was about 15 seconds, when used with a Thomson galvanometer which had a complete period of about four seconds. This is somewhat longer than usually experienced, and the explanation offered is that the retardation in attaining temperature uniformity in these large receivers is due to the slowness of the heat conduction from the extreme edges.

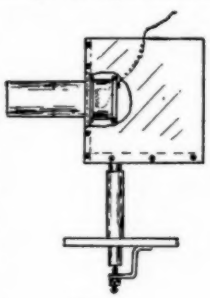

Fig. 4.
Thermopile Mounting

A glass window was used over the thermopile during the actual measurements for the determination of the mechanical equivalent, thus making the pile practically unsusceptible to drafts of air and to changes of background temperatures and other disturbances likely to be caused by the manipulation of the extensive apparatus used in the investigation. The transmission of this glass for the radiation used to calibrate the radiometer (see below), was determined by a separate measurement under the best conditions.

The mounting of the thermopile is shown in the detail sketch, Fig. 4. The protection to radiation and to convection currents is made very complete by the diaphragmed tube T and the enclosing box B, of bright tin. Still further protection is furnished by a large tin enclosing box indicated in the plan of the apparatus Fig. 2, and by the other portions of the screening system previously mentioned.

The auxiliary galvanometer used was of the d'Arsonval type, and was constructed by Leeds & Northrup. Its sensibility was 33 mm. per microvolt, its internal resistance 13.5 ohms, its external critical damping resistance 32.5 ohms and its period 7.5 seconds.

Although the thermopile resistance was very near the critical damping resistance and the thermopile was quite quick acting, it was found

[1] Coblentz, Bull. Bureau of Standards, 11, p. 131, 1914, also 9, p. 7, 1912.

[2] See fuller discussion, Bull. Bureau of Standards, 11, p. 131, 1914.

advisable to allow 45 seconds for the deflection to attain its maximum value before reading. This long period is attributable to the fact that the external resistance was not adjusted to meet the requirements for producing critical damping. In a thermopile the voltage attains about 90 per cent. of its maximum value in two seconds; while in tests on the d'Arsonval galvanometer, as ordinarily used, the maximum voltage is applied at once. The damping is no doubt different in the two cases.

In spite of the compensating construction of the thermopile there was a certain amount of slow drift (sometimes amounting to five per cent. of the deflection), due perhaps to the galvanometer. Any uncertainties due to these characteristics of the system were completely eliminated by the experimental procedure, which was as follows:

The thermopile was first exposed continuously for 15 or 20 minutes to radiation of about the value afterwards to be measured. Measurements when started were made on a time basis—the zero was read, a 45-second exposure was made, and then after another 45 seconds, the zero was again read. The zero used was the mean of the two readings. This procedure eliminated the effects of the slight drift except when this changed direction or rate during the reading, such a change, if large, being sufficient cause to discard the reading. (As it happens, during the final readings no drift change occurred which was considered of sufficient magnitude to call for discarding any readings, although the mean variation of the values would probably have been a little smaller had this been done wherever indicated.)

Another precaution taken was to keep all readings of very nearly the same magnitude. This was accomplished by the use of a sector disc over the ratiation standard. All possible errors due to slowness of deflection or variation from strict proportionality between stimulus and deflection (which there is no reason to expect) are avoided in this way.

The precision attained in making the radiometric measurements was very satisfactory, and is illustrated by the representative set of readings below, being the values obtained in the third run by method *C*.

Stimulus = .88 watt per square meter × window transmission (.777) × disc transmission (.2098) = .1432 watt per square meter.

Deflections in centimeters: 3.83, 3.84, 3.82, 3.83, 3.81.

Interval for reading on green radiation,

3.80, 3.76, 3.84,

Interval for reading on green radiation,

3.88, 3.85, 3.83, 3.82, 3.87.

The mean value is 3.83, from which watts per square meter per centimeter deflection = .03745.

The Radiation Standard.—The galvanometer scale was calibrated to give the intensity of the radiation stimulus in absolute value, by exposing the receiver of the thermopile to a standard of radiation, in the form of a seasoned incandescent lamp. This lamp had been standardized for the intensity of the radiant energy in absolute value, at a distance of two meters from the lamp, by direct comparison with the standard of radiation maintained at the Bureau of Standards.[1] This latter, maintained by a set of incandescent lamps, has been established by comparison against a black body, and also by direct measurement, in absolute value, of the energy radiated. The standard of radiation is thought to be accurate to better than 0.5 per cent. The lamp used in the present work was compared with the Bureau of Standards radiation standard before and after the completion of this research, and was found in agreement within one part in 700. The voltage and current calibration was also found in agreement, showing that the characteristics of the lamp had not changed. A further check was afforded by readings on a second radiation standard for which the transmission of the window over the thermopile was not determined. Assuming this to be the same as for the lamp used when both are at the same current, the watts per square meter per centimeter deflection were determined as .0370, to be compared with the mean value obtained from the chief standard (by many readings) of .372. The accuracy attained in the radiation measurements is believed to be quite as high as that in the photometric.

5. The Measurements.

The greater part of the time devoted to the final measurements was spent upon method *C*. This was done partly because of the independent value of the luminous equivalent of the green mercury radiation, partly because the variation in the value of the radiation from the arc with the consequent burden of simultaneous light and power measurements demanded much more attention and care. Three separate determinations were made by this method, between the first and second of which the apparatus was thrown completely out of adjustment and realigned from the start. Two determinations were made by method *B*, one immediately after the first and one after the third by the other method, using the sensibility values determined from them for the radiometer. No more were considered necessary because the possibilities for latitude in the result by this method lie not in the experimental measurements, which are extremely simple, but in the choice of luminosity curve, the measurements of the luminosity curve solution, etc.

[1] Coblentz, Bull. Bureau of Standards, 11, p. 87, 1914.

The individual readings are recorded in the tables. Under method *C* three sets of calculations are tabulated, namely, the luminous equivalent of one watt of mercury green radiation; the value of a watt of luminous flux in lumens according to the luminous efficiency ascribed to the green radiation from the Ives curve, and the same value when the Nutting curve is used.

These values are:

Lumens per watt of green mercury radiation	613.6
Value of one watt of luminous flux in lumens, Ives curve	616.7
Value of one watt of luminous flux in lumens, Nutting curve	622.2

The three sets of determinations agree to within one per cent.

Under method *B* two sets of calculations are given, one, the watt in terms of the lumen, using the Ives curve, the other, the same quantity as derived from the Nutting curve. The values are:

Value of one watt of luminous flux in lumens, Ives curve	563.6
Value of one watt of luminous flux in lumens, Nutting curve	613.4

The two sets of determinations were in practically perfect agreement.

For reasons given below these figures appear to be decisively in favor of the Nutting curve values. Giving equal weight to the values by the two methods, the value of the mechanical equivalent of light is:

$$1 \text{ lumen} = \frac{1}{617.8} = .00162 \text{ watt of luminous flux.}$$

6. Discussion of Results.

The Luminous Equivalent of the Green Mercury Radiation.—The value to be derived from these observations for the mechanical equivalent of light is dependent on the spectrum luminosity curve which is adopted. The value for the luminous equivalent of the green mercury radiation, on the other hand, is an independent experimental result, depending solely on the method of photometry and the value of the radiation standard. This value—613.6—is thus available for use with any luminosity curve determined by the same photometric method as that used to evaluate the green radiation as light. In view of the fact that all recently determined luminosity curves place the maximum luminosity of the equal energy spectrum close to .55 μ and give to wave-length .5461 μ an efficiency of at least 98 per cent. it appears safe to say that the mechanical equivalent of light is definitely fixed to within two per cent. by the determination of this constant.

The Agreement Between the Two Methods and Its Significance.—The agreement or disagreement of the two methods is quite independent of the radiation standard employed, and might in fact be studied with

any arbitrary working standard. It is dependent upon the self consistency of the photometric method used, upon the accuracy of the luminosity curve and upon the similarity of the visual characteristics of the groups of observers who determined the luminosity curve and the transmission of the monochromatic green solution. If the same group of observers had determined the luminosity curve and the transmission of the green solution then the agreement of the two methods would constitute a test of the accuracy of the luminosity curve and of the ability of the photometric method to add luminosities arithmetically. This latter has been previously established.[2] From our experience in the measurement of the monochromatic green solution we judge it extremely improbable that two groups of 18 observers would differ in their average characteristics as much as the difference exhibited by the two luminosity curves in question. There remains then only the question of the accuracy of the determination of these luminosity curves. That curve must be decided the more accurate which gives the best agreement between the two methods. This means the Nutting curve, by which the two methods agree to one and one half per cent., while with the Ives curve there is an outstanding discrepancy of about eight per cent. This difference between the curves, as already pointed out, is chiefly a difference in their area and may probably be traced back to the indirect means employed to determine the energy distribution in the earlier research.

But while the Nutting curve appears to be more correct, by this criterion, it must not be overlooked that this evidence is not alone sufficient to decide its entire correctness. All that is shown is that the ratio of the luminous efficiencies of the green mercury radiation and the "4-watt" lamp as given by this curve is approximately correct. A whole family of curves could be constructed which would meet this test. For instance, a similar curve with its maximum slightly shifted toward the blue would assign a higher value to the luminous efficiency of the green mercury radiation, which would lower the lumen equivalent of the watt of luminous flux; but this same shift would lower the luminous equivalent of the "4-watt" lamp, with a net result that the two methods would give results in closer agreement. Again, the luminosity curve is not as well determined as the transmission of the monochromatic green solution, as only a third the number of observers were used.

The final value of the mechanical equivalent must wait until all uncertainties in the luminosity curve are removed, but, as remarked above, the value can hardly be in doubt by as much as two per cent. unless some error is present in the green-line determination.

[2] Ives, "Studies in the Photometry of Lights of Different Colors," Phil. Mag., July, Sept., Nov., Dec., 1912.

The Weight to be Given to the Two Methods.—Having decided on the use of the values derived from the Nutting curve, the question comes up of the relative weight to be given to the two methods. The precision of both sets of measurements is so good that it is believed the outstanding difference is to be ascribed to the uncertainty of the luminosity curve, perhaps to the difference between it and the curve which would be obtained from the 61 observers who measured the green solution. The change called for might affect each value or both. Thus had the meas-

Method B.

1st Run:

Watts per cm., mean of 11 settings (mean deflection 3.83 cm.)..... .03745
Candle power of "4-watt" carbon lamp.....44.89
Corrected distance, source to thermopile..... .479 meters
Corrected deflection = Δ'. Ives, 1.30Δ; Nutting, 1.1975Δ.

Lumens per meter^2 $= \frac{44.89 \times .91}{(.479)^2} = 177.5.$

Watts per meter^2 $= \Delta' \times .03745.$

Working formula. Lumens per watt $= \frac{177.5}{\Delta' \times .03745} = \frac{4740}{\Delta'}.$

No.	Δ	Δ_I'	Δ_N'	Value of Watt in Lumens.	
				Ives.	Nutting.
1*B*	6.52	8.47	7.80	560	608
2*B*	6.42	8.35	7.67	568	618
3*B*	6.62	8.62	7.91	550	600
4*B*	6.51	8.48	7.78	559	609
5*B*	6.45	8.40	7.71	564	614
6*B*	6.38	8.30	7.62	571	622
7*B*	6.47	8.42	7.74	563	612
8*B*	6.45	8.40	7.71	564	614
9*B*	6.45	8.40	7.71	564	614
10*B*	6.39	8.31	7.64	570	620
				563.3	613.3 mean

urement of the monochromatic green solution been stopped at 30 observers, the mean would have been 1½ per cent. lower (perfect agreement). Had only the first 21 been taken (Nutting's number of observers) the mean would have been nearly as much lower. It has therefore seemed permissible to give the two values equal weight, remembering that they both lie within the range that would be calculated from the luminous equivalent of the green radiation by any recent luminosity curve.

Various Checks on the Order of the Magnitude of the Results.—A check on the order of magnitude of the result may be obtained by using various data on the efficiency and efficiency losses in incandescent lamps. The greater part of the power input in such lamps is transformed into radia-

tion, and such losses as occur can be fairly closely determined. A loss occurs due to conduction of heat away through the leading-in wires and filament supports. This loss has been measured by Hyde, Cady and Worthing[1] and amounts, in the case of a carbon lamp of the oval anchored filament type, operated at 4.85 w. p. m. s. c. to between four and five per cent. in efficiency. Another loss is caused by the absorption of radiation by the glass bulb. This absorption is much greater for the long-wave heat radiation than for light. The absorbed radiation is in part carried away by convection and conduction. Drysdale[2] found by experiment that this loss amounted to two or three per cent. of the applied power. Another part of the absorbed radiation is re-directed

2d Run:

Watts per cm. (13 settings, mean value 3.83 cm.) ..... .03745
Candle power of "4 watt" lamp 44.89
Corrected distance, lamp to thermopile ..... .564

$$\text{Lumens per meter}^2 = \frac{44.89}{(.564)^2} \times .91 = 128.0.$$

$$\text{Watts per meter}^2 = \Delta' \times .03745.$$

$$\text{Working formula. Lumens per watt} = \frac{128}{\Delta' \times .03745} = \frac{342}{\Delta'}.$$

No.	Δ	Δ_I'	Δ_N'	Value of Watt in Lumens.	
				Ives.	Nutting.
11*B*	4.63	6.02	5.54	568	617
12*B*	4.59	5.97	5.48	573	624
13*B*	4.67	6.08	5.58	562	612
14*B*	4.71	6.13	5.63	558	608
15*B*	4.65	6.05	5.56	556	614
16*B*	4.67	6.08	5.58	562	612
17*B*	4.70	6.12	5.62	559	608
				564.0	613.6 mean

as radiation of much longer wave-length. The distribution of intensity of this radiation around the lamp will be somewhat different from that of the light. It will be more nearly spherical, with a consequent still further loss of power in certain directions, notably the horizontal. This long-wave radiation will also suffer some loss by absorption through the air. There is, therefore, a difference to be expected between the total efficiency of an incandescent lamp of this type and its radiant efficiency of probably not less than seven or eight per cent.

The radiation standard lamp used is of the type of filament just described. It matches the candle-power standards at 103.5 volts. At this voltage it gives an illumination of 2.785 lumens per square meter at

[1] Trans. Illum. Eng. Soc., 6, p. 238, 1911.
[2] Proc. Royal Soc., A, 85, 275, 1911.

Method C.

1st Run:

Temperature at beginning, 21°; at end 22.5°, mean = 21.75°. . . . . $\theta = .989$

W, mean of eleven readings in three sets, during and at end of run (mean value of deflection 3.83 cm.). . . . . $= .03745$

$$\left(\frac{D_{c_1}}{D_s}\right)^2 = \left(\frac{.405}{.798}\right)^2 = .258$$

Working formula, $\frac{62.2 \times .258 \times .989}{\mu \times .03745 \times \Delta \times D^2}$, giving, lumens per watt

of green mercury radiation. . . . . $= m = \frac{424}{\Delta \times D_c^2}$,

ratio of the lumen to the watt of luminous flux, Ives curve. . . . . $= M_I = \frac{426}{\Delta \times D_c^2}$,

ratio of the lumen to the watt of luminous flux, Nutting curve $= M_N = \frac{430}{\Delta \times D_c^2}$.

	Δ	D_c	$\Delta \times D_c^2$	m	M_I	M_N
1*C*	1.47	.702	.726	584	587	592
2*C*	1.63	.647	.683	621	625	630
3*C*	1.85	.618	.707	600	603	608
4*C*	2.91	.487	.692	613	616	622
5*C*	3.48	.4455	.691	614	617	622
6*C*	3.80	.4275	.695	610	613	619
7*C*	3.93	.421	.697	609	612	617
8*C*	4.04	.418	.707	600	603	608
9*C*	4.04	.4415	.685	619	622	628
10*C*	4.05	.413	.691	614	517	623
11*C*	4.01	.414	.687	617	620	626
12*C*	4.02	.413	.686	619	622	627
13*C*	4.10	.4115	.695	610	613	619
14*C*	3.98	.4185	.697	609	612	617
15*C*	3.92	.4155	.677	626	629	635
16*C*	4.05	.417	.705	602	605	610
17*C*	3.91	.4195	.688	616	619	625
18*C*	3.95	.416	.684	620	623	629
19*C*	3.96	.4165	.687	617	620	626
20*C*	3.98	.4185	.698	607	610	616
				611.4	614.4	619.9 mean

two meters' distance. It also gives .975 watt per square meter at this distance. Hence its radiated lumens per watt = 2.858. The lumens per watt input = 2.597. The efficiency loss is therefore nine per cent. of the order of magnitude indicated by the considerations above. This measurement gives a check merely on the radiation standard. A check on the value for the mechanical equivalent is obtained by a supplementary measurement of luminous efficiency.

The large point-source carbon lamp at "4-watt" color was measured for radiant luminous efficiency by determining the ration of the radiant

power to the radiant power transmitted by the luminosity curve solution (the latter being, according to definition, luminous flux).[1]

Correcting for the actual transmission curve of the solution as compared with the Nutting curve, the radiant luminous efficiency was found to be .0045. Now .0045 times 417.7 is 2.78 = radiated lumens per watt. The lumens per watt consumption = 2.59. From this the efficiency

2d Run:

Temperature throughout 23° ..... $\theta = .982$

W, mean of 8 settings in two groups (mean deflection 3.88 cm.) ..... $= .0366$

$$\left(\frac{D_{c_1}}{D_s}\right)^2 = \left(\frac{.406}{.798}\right)^2 = .259.$$

Working formulas:

$$m = \frac{432}{\Delta \times D_c^2},$$

$$M_I = \frac{434}{\Delta \times D_c^2},$$

$$M_N = \frac{438.5}{\Delta \times D_c^2}.$$

	Δ	D_c	$\Delta \times D_c^2$	m	M_I	M_N
21*C*	3.43	.456	.714	607	610	614
22*C*	5.41	.360	.702	616	619	625
23*C*	5.88	.342	.688	629	632	637
24*C*	6.03	.338	.690	627	630	635
25*C*	6.12	.340	.708	611	614	619
26*C*	5.99	.346	.717	603	606	611
27*C*	6.06	.3395	.699	619	622	627
28*C*	5.84	.345	.696	622	625	630
29*C*	5.91	.3455	.706	612	615	621
30*C*	5.98	.3465	.719	602	605	609
				614.8	617.8	622.8 mean

loss is seven per cent.—a satisfactory check with the other values. This check is of course practically method *B*, except that the power transmitted by the luminosity curve solution is obtained indirectly by two separate experiments.

The Reproducible Character of the Measurements Given.—A feature of the work here reported, which is believed worthy of emphasis, is that unlike most previous measurements of a similar nature, every element entering into the result may be copied and checked by other observers. The determination is, in short, of a strictly reproducible physical character. This is made possible by recording the factors most difficult to measure in material standards of reproducible or maintainable form.

[1] A set of determinations of luminous efficiency have recently been made in this manner by Karrer, PHYSICAL REVIEW, p. 189, Vol. V., N. S., No. 3, 1915.

Thus the difficult measurement of green light is recorded in the reproducible green solution. The measurement or radiation in absolute value is confided to long-lived incandescent lamps. If in the future either the standard of radiation is changed, or the photometric method here employed is superseded, the ratio of the new to the old value can be applied directly to the value obtained in this investigation without the necessity for repeating the whole piece of work.

The chief uncertainties in the result are on the physiological side,

3d Run:

Mean temperature 21.5° ..... θ = .991

W, mean of 13 settings (mean deflection 3.83 cm.) ..... = .03745

$$\left(\frac{D_{c_1}}{D_s}\right)^2 = \left(\frac{.404}{.798}\right)^2 = .256.$$

Working formulas:

$$m = \frac{421}{\Delta \times D_c^2},$$

$$M_I = \frac{423}{\Delta \times D_c^2},$$

$$M_N = \frac{427.5}{\Delta \times D_c^2}.$$

	Δ	D_c	$\Delta \times D_c^2$	m	M_I	M_N
31*C*	3.11	.4675	.680	620	623	629
32*C*	4.14	.405	.680	620	623	629
33*C*	4.68	.380	.677	622	625	632
34*C*	4.75	.381	.690	610	613	619
35*C*	4.76	.3785	.682	618	621	627
36*C*	4.62	.384	.681	619	622	628
37*C*	4.54	.387	.681	619	622	628
38*C*	4.61	.386	.687	614	617	622
39*C*	4.64	.386	.692	609	612	618
40*C*	4.56	.386	.680	620	623	629
				617.1	620.1	626.1
Mean of all observations (*c*)				613.6	616.7	622.2

which is here relegated to entirely independent investigations. A general agreement on photometric methods, a definite answer to the question: "What is light?" by the establishment of a representative average eye spectrum luminosity curve—there lies the work of the future. When that is completed the chief uncertainty of the present work can be removed. This uncertainty is however believed to be quite small.

7. SUMMARY.

The subject matter of this paper may be summarized as follows:

1. Rational definitions have been given for light quantities. In

accordance with these the mechanical equivalent of light is defined as the value of the lumen in watts.

2. An experimental determination by two different methods gives for the mechanical equivalent of light a mean value of 0.00162 watt per lumen.

The discussion of the significance and importance of this quantity may be brief by reason of the full discussion in the various publications to which reference has been made. Suffice it to say that here luminous flux, on the basis of the accepted definition, can be measured in C.G.S. units, *e. g.*, in watts, and that consequently the watt is a rational standard of luminous flux ("primary standard of light").

The measurement of luminous flux in watts and the establishment of the watt as the standard are dependent on the evaluation of the present standard and units in terms of the watt. The mechanical equivalent of light is therefore the most fundamental quantity in the establishment of light measurement on a physical basis.

PHYSICAL LABORATORY,
THE UNITED GAS IMPROVEMENT COMPANY,
PHILADELPHIA,
December, 1914.

THE CORONA IN AIR AT CONTINUOUS POTENTIALS AND PRESSURES LOWER THAN ATMOSPHERIC.

BY DONALD MACKENZIE.

SINCE the practical importance of the corona discharge was first realized, the subject has been extensively investigated both in this country and abroad.

The general agreement among observers is that the corona-forming voltage is independent of the material of the discharging conductor and of the humidity of the air; that the critical surface-intensity is greater for smaller wires; that increased temperature or decreased gas pressure decreases the critical voltage; and finally, that the onset of the phenomenon is not affected by the antecedent ionization near the wire.

It was with a view to examine the continuous potential corona at low pressures and so to test the extension of the empirical laws found for the alternating corona that the work here reported was begun. In this laboratory at the present time the only available source of direct current at high potential is a battery of 500-volt, 0.1 kilowatt generators driven by a direct current motor. These generators are separately excited from a lighting circuit, which also furnishes power to the motor; this makes the control of voltage very difficult, the fluctuations in the line voltage amounting at times to three or four per cent. Most of the irregularities of the points plotted for some of the curves are attributable to this condition. The speed control of the motor enables the generated voltage to be raised to more than 900 volts on each machine: at the beginning of the work five such generators were at hand, furnishing a potential of 4,000 volts and more, but two machines broke down before much progress had been made. This limited the total voltage to 2,700 volts, and so placed a regrettable restriction on the dimensions of the corona apparatus and the pressure range.

DESCRIPTION OF APPARATUS.

A diagram of the apparatus used is shown in Fig. 1. *A* is a large glass tube 10 cm. in diameter and 75 cm. long, inside of which is supported by hard rubber rings the brass cylinder *B*, 4.9 cm. in internal diameter and 61 cm. long. These rings are pierced with a number of holes to permit

free flow of air through all parts of the apparatus. The glass cylinder is closed at each end by brass plates, cemented on with a mixture of beeswax and rosin. In the center of each of these plates a hole is drilled, permitting the passage of the wire *C*, which is soldered at each end into bushings held by the nuts *DD*. In all cases it was easy to apply sufficient tension to hold the wire straight unless a large current was allowed to pass in the discharge.

The glass tube *A* is provided with three side tubes, two of which serve for the ground connection to the brass cylinder and for the pump connection respectively. The third side tube, the uppermost in the figure,

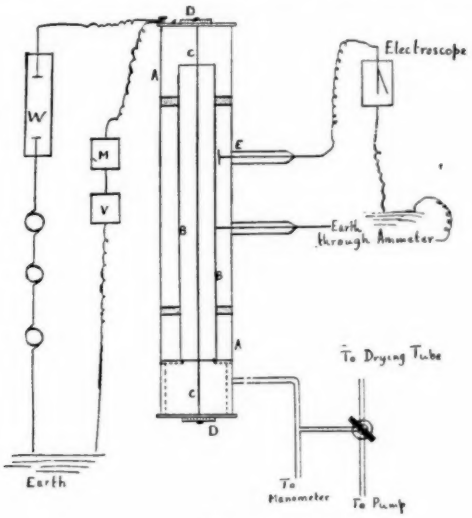

Fig. 1.

Diagram of corona apparatus.

supported another glass tube, sealed into it with sealing wax and drawn down at each end to hold a small brass rod screwing into a brass plate about 2 cm. in diameter. Connection to ground and to the brass rod just mentioned was by small platinum wires sealed directly into the glass tubes. The disk carried on the end of the brass rod *E* is curved parallel to the surface of the brass cylinder, and stands about a millimeter above it. Directly under the disk are a dozen or more small holes in the cylinder, through which charged particles may pass on their way out from the central wire, charging or discharging the electroscope to which the disk is connected.

The voltage of the three generators is applied to the apparatus over leads including the water resistance *W*, about 3 cm. in diameter and 75 cm. long, variable by varying the separation of platinum electrodes.

One end of the generators is connected thus to the brass plate closing the glass tube; the other end is earthed, as is the brass cylinder through a milliammeter or galvanometer. Reversal of wire polarity is effected by reversing the excitation of the generators. Measurement of voltage is by means of a Weston D.C. voltmeter V with a multiplier M, reading 150 volts when the wire potential is 3,000.

The apparatus is supported vertically on a table, from which it is insulated by porcelain blocks. To prevent the breaking of the ground connection by slipping of the corona tube, the latter is supported on a hollow wooden cylinder, the walls of which are turned very thin except at the top, where a ring supports the lower end of the brass tube. In immediate contact with the tube is a thin ring of hard rubber; this ring extends into the field no more than a millimeter, and in no case was any irregular behavior of the discharge caused by its presence.

In the upper brass plate are cut holes covered with glass windows. Above these is fixed a mirror permitting visual exploration of the space within the cylinder.

It was expected that a charged electroscope connected with the disk E would be affected by a discharge passing between the wire and the cylinder: a positive corona on the wire should discharge a negatively charged electroscope and vice versa. This expectation was justified: when the corona starts the gold-leaf drops instantaneously and there is no possibility of confusing this effect with a loss of charge due to atmospheric leak. As the voltage is raised, electrostatic induction brings about a partial fall of the gold-leaf: a negatively charged gold-leaf receives an induced positive charge in the presence of the positively charged wire, the corresponding negative charge appearing at the disk E. As long as the potential of the wire is constant the magnitude of the induced charge on the electroscope does not vary, and the definiteness of the observation is not diminished by this action.

The electroscope is charged statically, and the voltage gradually raised until the gold-leaf suddenly falls. The voltmeter is then read and the pressure recorded.

The wires used were carefully straightened by the electric current, except in the case of the larger wires, which were brass rods free from kinks. All were polished with fine emery and crocus cloth, and when put into the tube showed no sign of surface irregularity. Dust particles from the air settling on the wire are of no importance, since unless the wire is sticky they are driven off by electrostatic repulsion. This fact has been overlooked by most observers, who attribute irregular behavior of the corona to dirt which they suppose to have settled on the wire.

The most important step in setting up the apparatus is the centering of the wire in the brass cylinder. The method used is as follows: The end bushings pass through quarter inch holes in the end plates which allow sidewise displacement of the whole wire. When the nuts are tightened to give the tension considered suitable, a scale is placed under the apparatus lying horizontal on the table. The eye is held steady over the scale, which lies just parallel to the end of the brass cylinder. Placing the head at such a distance above the tube that the cylinder subtends at the eye a given number of scale divisions, say 2.5 in., it is possible to judge how far from center is the wire: if the tube covers 2.5 in. on the scale the wire should stand over the 1.25 in. division. If such is not the case, adjustment is made by moving the nut across the end plate, and the apparatus is then turned through 90 degrees to make a second adjustment at right angles to the first. Then the previous adjustment is re-examined and corrected if necessary, and the procedure repeated at the other end. The cylinder of wood at one end of the tube hides the wire, but by gently tapping the end plate opposite, the brass tube can be induced to move away from the wooden ring sufficiently far to permit centering. Then, when both ends are satisfactorily adjusted on the axis of the cylinder, the apparatus is ready for installation. It was found a simple matter to set the wire to 1/200 in.

When the tube has been set in place the air is exhausted by means of a Gaede pump and the space refilled with air drawn through a column of sulphuric acid to exclude moisture. This is repeated a number of times, and the apparatus left exhausted to allow leaks to manifest themselves. With the number of beeswax and rosin seals necessary, leaks could not absolutely be avoided, but they could usually be kept so slight that no alteration in the reading of the manometer could be detected in the time spent in making observations at any one point. When the leakage was faster than this, it was possible to estimate its magnitude and correct the pressures recorded. This occurred in only one case, which will be described later. The pressure was read on a closed mercury manometer connected immediately to the glass tube.

Preliminary Experiments.

The first experiments were made with large wires, 3/32 in. in diameter. The voltage then available was 4,000, and corona formed on such wires at a pressure of about 4 or 5 cm. At once a difference was noted in the positive and negative discharges. With the wire positive, the corona formed at a definite voltage and pressure, disappearing as soon as the voltage was lowered or the pressure raised by the smallest step that

could be made. With the wire negative, however, the discharge was of quite different form. At a given impressed voltage, no visible discharge passed until the pressure was lowered well below the value corresponding to the positive corona at the same potential. Finally, however, came on a discharge carrying a large current sufficient to burn out two 16-c.p. incandescent lamps in series in the ground connection. This discharge persisted after the voltage was lowered far below the initial value, and was not extinguished by a moderate increase in pressure. In fact, a discharge setting in, say at 3,500 volts and 4 cm. pressure, persisted up to a pressure of more than 26 cm. Increase in pressure was accompanied by an increase in the current flowing; even at low pressure sufficient heat-energy was liberated to make the glass tube uncomfortably warm.

The water resistance had not been used. It was then inserted in the high potential side in order to keep the current down to a value safe for the generators. On examining the discharge from the negative wire, it was seen to show the characteristic structure of the discharge in high vacua. The appearance will be described presently. Instead of a uniform glow along the whole wire as in the positive effect, the luminosity is confined to a small length of the negative wire.

With the large wires it was possible to obtain the positive corona at the lowest pressures attainable (from 1 to 2 mm.) but the negative corona never appeared: the discharge from the negative wire was always of the vacuum tube type. On removing the wire from the tube it was found deeply oxidized at the points where the vacuum tube discharge had existed.

This singularity is intimately associated with the size of the wire, as will appear from the experiments about to be described.

FINAL RESULTS.

1. *The Positive Effect.*—All of the wires when positive to the tube form coronas at the lowest pressures to which the apparatus was evacuated. The discharge is a perfectly uniform and stable violet or bluish glow extending the whole length of the wire within the brass cylinder. Using the electroscope charged negatively, the gold-leaf is seen to fall sharply at a definite voltage, and keeping the pressure constant this value of voltage may be read any desired number of times. The recorded observations frequently show a disagreement of 20 volts among the readings repeated at a constant pressure: this disagreement is due not to any irregular behavior of the corona, but to the fluctuations in the voltage of the circuit supplying the generators and motor. In the time taken for the observer to note the fall of the gold leaf and thereafter read the voltage,

the voltmeter needle may move in one direction or another and then rest for several seconds. Variations of two or more scale divisions are not uncommon: these mean a variation of 40 to 50 volts in the potential of the wire. When two observers work simultaneously, one noting the electroscope and the other reading the voltmeter, these irregularities do not affect the observation.

It was invariably found for the larger wires that the onset of the visible corona accompanied the discharge of the electroscope. The corona is faint at onset and around small wires can be seen only with well rested eyes; however, it is seen whenever attempted under suitable conditions. Having once verified this expected result I relied thereafter upon the electroscope. With each wire the verification was repeated.

As the voltage is raised above that necessary to start the corona, the luminous sheath expands progressively, accompanied by an increase in the current making the latter readable on the milliammeter. With further increase in voltage a point is reached where the corona is unstable. A slight increase in voltage causes the corona, previously uniform over the whole length of the wire, to collapse to a vacuum tube discharge confined to a few millimeters. The instability of the corona at this transition point is shown by the fact that if the generator excitation and motor speed are kept at the appropriate value and the potential suddenly applied to the wire, corona forms for an instant and then collapses to the vacuum tube discharge. Refilling the tube with cool air and then exhausting anew lengthens the time taken for the change to 4 or 5 seconds. This lag could not definitely be determined owing to the variations in generator voltage. On the establishment of the vacuum tube discharge, the voltage drops 50 or 60 per cent. and simultaneously the current rises to many times its former value.

This form of discharge shows all the structure recognized in the vacuum tube discharge. The negative glow is a thin blue layer against the inner wall of the brass tube, separated from it by a narrow Crookes dark space. The positive column is a pink sheath enveloping (usually, but not always, completely) a centimeter or two of the wire, directly opposite the negative glow which does not go completely around the inner surface of the cylinder but covers an increasing circular extent of it with increasing voltage. Between the positive column and the negative glow is the Faraday dark space; at low currents (total voltage over corona tube and ballast resistance lowered) this space is invaded by the positive column, which becomes striated. Further lowering of the voltage causes the striations to become more distinct, and the positive column extends almost to the point of meeting the negative glow; the latter is greatly

diminished in extent and brilliancy. At last, just as the Faraday dark space seems to be completely eliminated, the discharge ceases. The same sequence of phenomena is seen when the pressure is allowed to increase. After cessation of the discharge the voltage between the wire and tube rises to the value appropriate to an inactive field.

Increasing the total voltage increases the current carried; the voltage on the tube and wire slowly decreases. Decreasing total voltage decreases the current at the same time that the tube-wire voltage gradually increases.

2. *The Negative Effect.*—For the larger wires used in my experiments the negative corona is not obtainable: the first detectable discharge is the vacuum tube discharge. For the smaller wires the case is different. At the lowest pressures the vacuum tube discharge is the only one obtainable. At higher pressures the negative corona appears, expands with increase of voltage above the critical value, and gives place to the negative vacuum tube discharge at a transition point determined, as in the positive effect, by the pressure and the wire diameter. After the vacuum tube discharge has been established the current and tube-wire voltage vary as in the positive effect. The cessation of the discharge is after the same sequence of changes in the two cases.

The negative corona is never a uniform sheath like the positive. It is grouped about bright blue points set at intervals along the wire; these blue points are surrounded by reddish streamers, and increase in number as the voltage increases. With decreasing voltage the blue points are the last to disappear: they persist at a voltage lower than that at which they form.[1]

After transition, the structure of the discharge is the same as the positive vacuum-tube discharge, but reversed: next to the wire is the Crookes dark space surrounded by the negative glow, cylindrical in form; then comes the Faraday dark space and after it the positive column flat against the surface of the tube.

The negative glow may appear outside the uniform field, at the very end of the wire—the positive column collecting in a restricted area at the edge of the brass tube. The discharge may start in the interior and climb up more or less rapidly to the end of the wire. This is probably due to convection currents, set up even in rarefied air by the very hot discharge. This explanation is suggested by the fact that if the voltage is suddenly removed and reapplied, the renewed discharge prefers points

[1] Since these observations were made, experiments by Farwell have shown that the negative corona is invariably that described above, and that the number of the blue points on the wire is characteristic of the voltage. Farwell, PHYS. REV., 4, 2d Series, 31–39, 1914.

which have just previously been discharging. It is reasonable to suppose that the air in this neighborhood is in a favorable condition to initiate the discharge, being adjacent to the most highly heated portion of the wire. Convection currents raise this hot air, making conditions less suitable at the lower end and more so at the upper end of the existing discharge column.

The energy of the discharge is sufficient to heat to redness the wire and partially to oxidize the wall of the tube: after prolonged discharge a green color is seen in the field. In both positive and negative effects at very low pressures (for this apparatus) the Crookes dark space is seen to lie over a negative layer. This luminosity adjacent to the cathode, accompanying the ionization of the gas by the canal rays, is more readily recognized at low pressures because of the greater length of the Crookes dark space.

Description of Observations.

The observations at each point were considered satisfactory if no readings of the voltmeter differed from the mean by more than one half a volt; this variation was unavoidable because of fluctuations. The multiplier ratio being 20 to 1, this means that a disagreement of 10 volts was considered tolerable. The accuracy of the observations may be judged from the following table, showing some of the readings for the negative corona on a nickel wire, diameter 0.063 cm.:

Pressure in mm.	Voltmeter Readings.	Voltage.	Pressure in mm.	Volmeter Readings.	Voltage.
69.8	124.0	2,480	56.5	110.0	2,200
	123.8	2,476		110.0	2,200
	123.0	2,460		110.0	2,200
	124.0	2,480		110.0	2,200
62.5	116.5	2,330	48.2	101.0	2,020
	117.5	2,350		100.0	2,000
	117.0	2,340		100.0	2,000
				101.0	2,020

Wires of diameter 0.165 cm., 0.157 cm., 0.107 cm. and 0.063 cm. were all investigated using the electroscope as a detector of the onset of the corona. For the negative effect when no corona can be formed, visual observations were relied on: the behavior of the electroscope is irregular when the tube is sustaining a vacuum tube discharge unless the region involved lies directly under the disk E: in this event the positively charged electroscope is immediately discharged and then receives a negative charge.

When associated with the smallest wire, 0.042 cm. in diameter, the electroscope gave evidence of an ionization current unaccompanied by luminosity. At pressures even higher than one-half an atmosphere, the charged wire had an influence on the electroscope. Several electroscopes

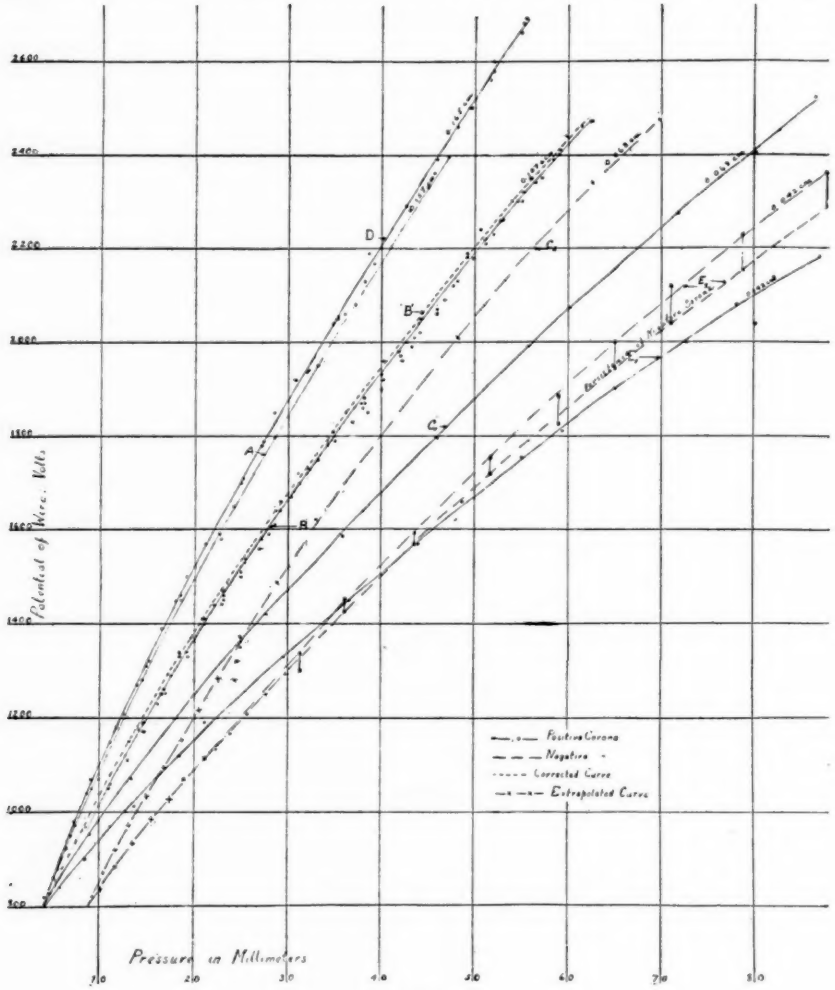

Fig. 2.

Corona-forming voltage. Diameters: A, 0.157 cm. +; B, 0.107 cm. +; B^1 is B corrected or leak; C_1, 0.063 cm. +; C_2, 0.063 cm. −; D, 0.165 cm. +; E_1, 0.042 cm. +; E_2, 0.042 cm. −.

of different form and size were tried, but all behaved in the same way: the electroscope charges spontaneously, the sign of the charge being positive when the wire is positive, negative when the wire is negative. The more sensitive electroscope charged until the gold leaf touched the

grounded case inclosing it, after which it fell back and the process repeated itself continuously.

Accordingly, the attempt to detect corona formation by the electroscope was given up for this size of wire, and in place of the milliammeter there was substituted a galvanometer, giving a deflection of one scale division for 7×10^{-6} amperes. The suitability of the galvanometer for this work (at least under these conditions) is shown by a comparison of curves A and E_1, Fig. 2.

Observations with the galvanometer are made as follows: The observer watches the galvanometer, at the same time slowly raising the voltage, and at the first perceptible deflection of the needle he reads the voltmeter. The experiment is repeated until the observer becomes accustomed to noting very small deflections and has convinced himself that they occur at the same value of voltage each time, and are simultaneous with the appearance of the corona. He then proceeds with the same program as when using the electroscope.

Curve B, Fig. 2, is plotted from observations on a steel wire of diameter 0.107 cm. During these observations the leak of air into the apparatus was quite rapid and efforts to overcome it failed. Accordingly it was decided to let the apparatus leak and make observations in the following way: The electroscope was charged, the voltage raised until the gold-leaf fell, then the pressure read immediately and the voltmeter last. As soon as possible the electroscope was re-charged and the series of operations repeated. This gave a new pressure reading, by reason of the leak during the interval between the two observations. Five series of such observations were made and all observations plotted on the sheet. Through them a smooth curve B was drawn, and this curve corrected for leak. The following considerations enabled the correction to be made:

The pressure rises 5 cm. in ten minutes, or 5 mm. per minute. The time taken to note the discharge of the electroscope and read the manometer is approximately six seconds or one tenth minute. In this interval the pressure has risen 0.5 mm.—it is that much higher than it was at the instant the electroscope was discharged. The correction, then, is to shift the plotted curve to the left on the sheet through a distance corresponding to 0.5 mm. in pressure. Curve B', Fig. 2, results.

Special investigation was made to determine the influence of temperature variation on the corona-forming voltage. It was found that within the limits of variation of room temperature during observations (19° to 21° centigrade), such as influence is not appreciable.

COMMENT ON CURVES.

The intersection of the positive corona curves by the negative curves for the same wires is of the greatest interest. It has been suspected for some time that under certain circumstances the positive and negative coronas begin at different voltages. The difference varies with the size of wire and the pressure. In the case of each of the two wires for which observations of the negative corona were possible, there is a pressure below which the positive critical voltage is higher than the negative, while above this pressure the negative starts at the higher voltage.

The intimate relationship of the negative corona to the pressure and the size of wire is well shown in the curves. The 0.063 cm. wire forms a stable negative corona only at pressures above 25 mm. The 0.042 cm. wire gives a stable negative corona as low as 19 mm. This peculiarity of the negative corona has not, it is believed, been heretofore recorded.

The lower curve E_2 of Fig. 2 represents the observation that as the voltage is gradually lowered below that corresponding to the first deflection of the galvanometer needle, the negative corona persists for a time. The interval of voltage during which it continues to be observable on the galvanometer is indicated by the vertical lines.

E. A. Watson[1] has worked with the corona in cylindrical fields. He was able to use continuous potentials up to 70,000 volts, derived from an influence machine of special design. The wires used ranged in diameter from 0.070 cm. to 1.276 cm., and the pressure was varied from atmospheric down to 35 cm. He describes the same difference in the appearance of the two coronas as that observed here and finds that the negative corona starts at a higher voltage than the positive on the same wire. Watson found no region of pressure where the negative corona failed to appear.

V. Schaffers[2] has studied the continuous potential corona at atmospheric pressure, using extraordinarily small wires, 0.0003 cm. to 0.35 cm. He concludes that the ratio of the potentials critical for the positive and negative coronas varies regularly with the radius of the wire: for $r = 0.01$ cm. the two potentials are equal; for r less than this, the negative is lower than the positive; for r greater than 0.01 cm. the positive is the lower. These results refer to atmospheric pressure only, but tend to confirm Watson's observations and those of the present paper.

Investigators of the alternating corona have usually thought that the corona forms on the two half waves at the same value of instantaneous voltage. This conclusion is rendered doubtful by the experiments of

[1] Electrician, *63*, 828, 1909, and *64*, 707, 1910.

[2] Comptes Rendus, *157*, 203–206, 1913.

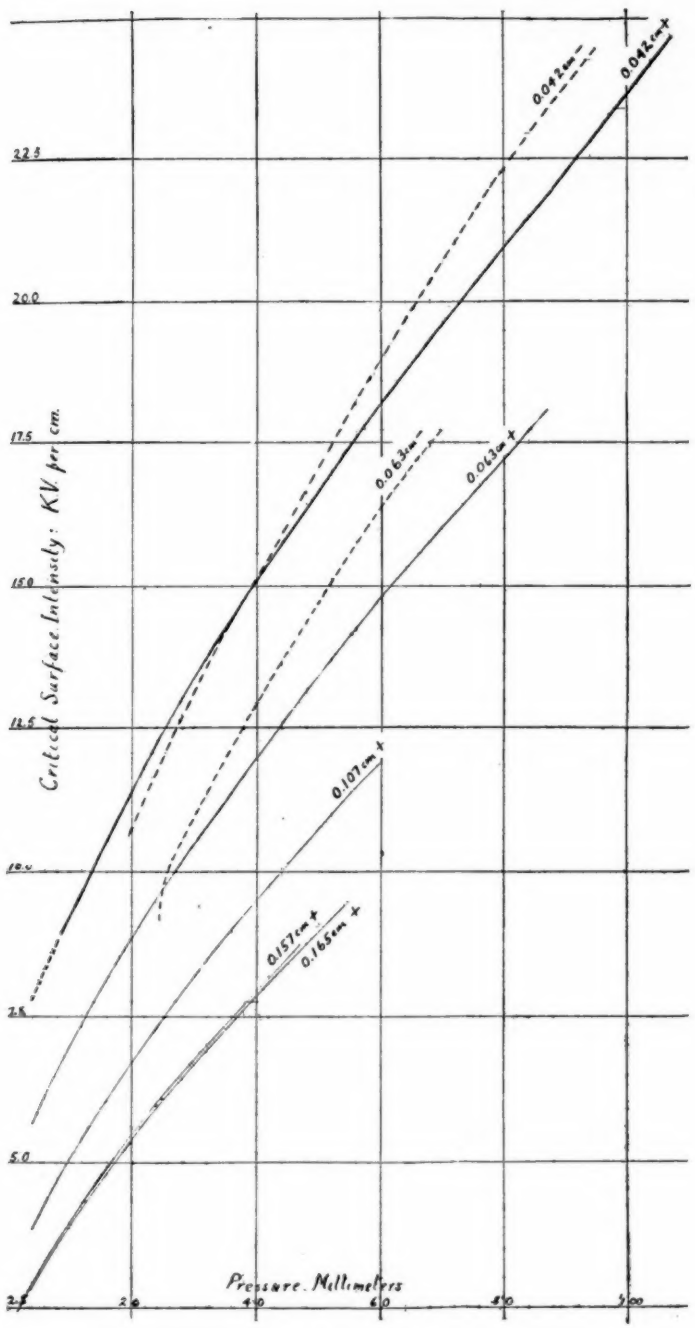

Fig. 3.

Critical surface-intensity. Solid curves indicate positive corona; dotted curves indicate negative corona.

Bennett,[1] who made an oscillographic study of the corona-current and voltage. When no corona discharge is taking place, the current oscillogram records only the charging current of the apparatus,—a pure sine wave. As the voltage is gradually raised to the critical value, the charging current recorded by the oscillograph remains a sine wave until the corona voltage is reached. At this point the charging current is broken by humps: a smooth hump for the positive corona, an oscillatory disturbance for the negative. Also the negative hump is more pronounced. This is in accord with the observations made here when using the galvanometer to detect the corona. It was found that the least perceptible deflection of the needle was a small fraction of a scale division for the positive corona; for the negative, however, the swing is through several scale divisions no matter how carefully the voltage is raised.

If it is true that one corona forms at a lower voltage than the other, then if the pressure and voltage are appropriate the corona tube should rectify the current due to an alternating potential. An experiment to test this was carried out with a 20 : 1 transformer, excited by 110 volts, 60 cycles. The pressure was adjusted to 85 mm. around the wire of 0.042 cm. diameter. This pressure corresponds for this wire to a positive critical potential lower than the negative. On closing the secondary circuit of the transformer and raising the voltage to the critical value, a steady deflection of the galvanometer needle occurs, corresponding to a positive current, *i. e.*, from wire to grounded cylinder. With increase in voltage the deflection is reversed: the negative current is larger than the positive. Thus the corona tube acts as a rectifier, the sign of the rectification depending on the value of the impressed voltage. No facilities were available for making a thorough investigation of the relation of galvanometer deflection and maximum value of the alternating voltage; it is hoped that this may be carried out in the future.

The above experiment was suggested by Dr. J. A. Anderson.

This was almost anticipated by an experiment of Dr. J. B. Whitehead.[2] In 1911 he reported to the American Institute of Electrical Engineers his observations of the ionization due to alternating currents in the corona tube. The method used was this: A woven wire cylinder was the grounded electrode, and was surrounded by a solid cylinder of metal connected through a D'Arsonval galvanometer to a source of continuous potential, the other D.C. electrode being grounded. At start of corona an excess of positive ions reaches the detector; at higher alternating potentials the excess is of negative charges. This should be interpreted

[1] Proceedings A. I. E. E., XXXII., 1473–1494, 1913.
[2] Ibid., XXX., 1857–1887, 1911.

to mean that the positive corona appears earlier, whereas when the negative corona is formed the ionization accompanying it is far more intense than that belonging to the positive half cycle. Dr. Whitehead, however, does not speak of the rectifying effect of the corona discharge: this would have been found had the galvanometer been in the A.C. circuit.

The theory of secondary ionization has been applied to the corona by Townsend.[1] His formula is verified by Watson's results. According to Townsend

$$kv = P\left(30 + \frac{9}{\sqrt{aP}}\right),$$

where P is the pressure in atmospheres and a the wire diameter.

An empirical law has been proposed by Peek[2] to comprehend the results of work on pressure and temperature. His equation is

$$g = 31\delta\left(1 + \frac{.3}{\sqrt{r\delta}}\right),$$

where g = critical surface intensity in kilovolts per cm.,

r = radius of wire,

δ = "density factor," $= 3.92p/(273 + t)$: p is the pressure in centimeters, t is the temperature centrigade.

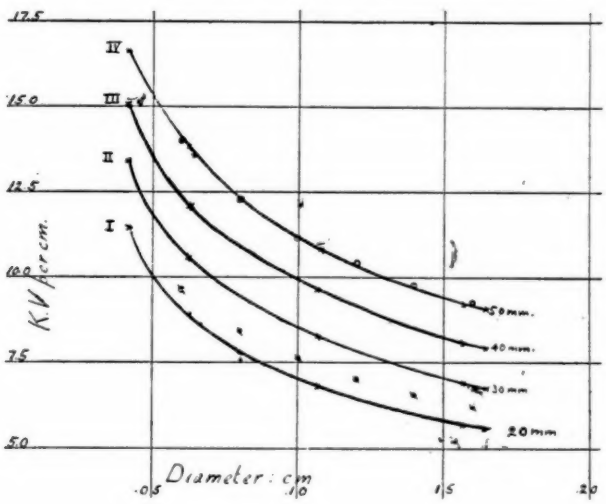

Fig. 4.

Critical surface-intensity and diameter of wire. Positive corona. Temp. = 21.°0 C. Circles indicate points plotted from Peck's law to compare with Curve III., $\delta = .0533$, $p = 4$ cm.; crossed circles indicate points plotted from Peck's law to compare with Curve I., $\delta = .0267$, $p = 2$ cm.

[1] Electrician, *71*, 348, 1913.

[2] Proceedings A. I. E. E., XXX., 1889–1963, 1911; XXXI., 1051–1092, 1912; XXXII., 1337–1355, 1913.

On Fig. 4 are plotted points derived from this equation for $t = 21$ degrees and $p = 2$ cm. and 4 cm.

The comparison shows that the computed curves differ from the observed numerically but not in form—the difference being a function of the pressure but independent of the diameter of wire. Further observations are necessary to enable a suitable correction term to be determined.

Transition points at various pressures are shown in Fig. 5 for two wires. At the left in Fig. 5 is the curve of transition point for the positive corona,

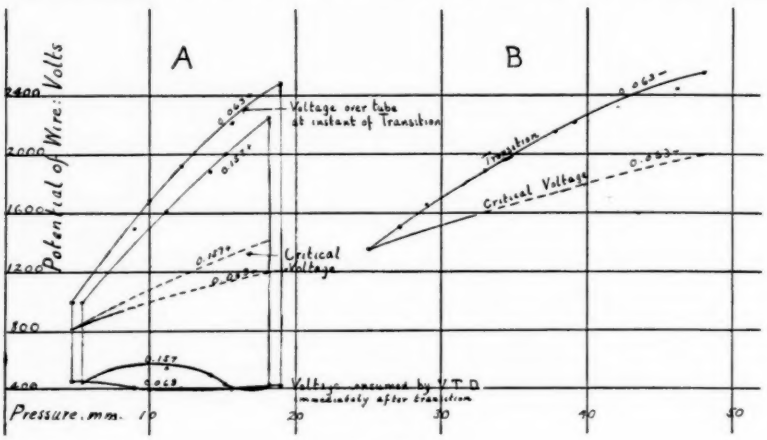

Fig. 5.

Voltage of transition from corona to vacuum-tube discharge. *A*, Positive effect, wires of diameter 0.157 cm. and 0.063 cm.; *B*, Negative effect, 0.063 cm. wire. Critical voltages shown in dotted curves.

at the right that for the negative. The straight vertical lines in the positive figure represent the instantaneous drop in tube-wire voltage attendant upon the transition from corona to vacuum-tube discharge,—no such observations were made in the work on the negative corona. The ordinates of the upper curve are the voltages at which transition occurs; those of the lower curve are the voltages consumed by the vacuum-tube discharge immediately after the transition. The critical voltages are shown in dotted curves.

In the case of the negative wire at pressure 24.5 mm. the curve of transition point intersects the curve of critical voltage. At this pressure the range of the negative corona on this wire is so narrow as to be within the voltage fluctuations. The observations do not establish such a point for the positive corona.

Conclusion.—It seems unprofitable to speculate on the nature of the corona until it has been more thoroughly studied. Observations at

atmospheric pressure and at pressures considerably below the atmosphere have yielded empirical equations which require modification to enable them to include the results reported in this paper. The ionization current which in the case of small wires exists before the luminous discharge begins, the transition from corona to vacuum-tube discharge, the dependence of the stable negative corona on the wire size and on the pressure,—all these questions call for extended investigation.

The principal results of the work described in this paper may be briefly enumerated as follows:

1. The formation of the stable negative corona has been shown to be dependent upon the pressure and the size of conductor. Of the wires used, with those of larger diameter such a corona is never formed, while around the smaller wires the negative corona can exist only at pressures greater than a critical value which varies with the diameter of the wire.

2. The transition has been observed from the stable corona to the vacuum-tube discharge. The vacuum-tube discharge is the only luminous discharge with negative wires below the critical pressure.

3. Curves have been plotted of critical surface intensity for the positive corona and wire diameter at various pressures. These curves are similar in form to those of Peek's equation

$$g = 31\delta\left(1 + \frac{.3}{\sqrt{r\delta}}\right).$$

Values calculated from this equation differ from those observed by a quantity which is a function of the pressure but independent of the diameter of the wire. The observations are not sufficiently numerous to determine the correction to the formula.

4. The ratio of the critical voltages for the positive and negative coronas on a given wire varies with the pressure. A pressure exists at which the two critical voltages are equal; below this pressure the negative critical voltage is lower than the positive, at higher pressures the positive corona-forming voltage is the lower.

5. The corona rectifies an alternating current, the direction of the rectified current depending on the voltage and the pressure.

6. In the case of the smallest wire evidence has been found of the existence of an ionization current flowing before the appearance of the luminous discharge.

It is a pleasure to acknowledge the indebtedness I am under to those who have assisted me in this undertaking. The work was begun at the suggestion of Dr. J. B. Whitehead, and his published papers have been

constantly consulted. My particular thanks are due to Professor Ames, who has aided and encouraged the work in every possible way. Valuable assistance has been received from Dr. J. A. Anderson and Mr. M. W. Pullen. I am grateful as well to my fellow student, Mr. S. M. Burka, for his kindness in the matter of glass-blowing and to Mr. Frank Smith for his careful mechanical work.

JOHNS HOPKINS UNIVERSITY,
BALTIMORE, May, 1914.

ON THE EXTRACTION AND PURIFICATION OF RADIUM EMANATION.

By William Duane.

DURING the last few years a great many investigations have been made on the effects produced by relatively intense beams of Becquerel rays. The most efficient known sources of these rays consist of a small tube containing a considerable amount of radium emanation, or of a large deposit of radium *B* and *C* on a surface of small area. The author has constructed hundreds of such "radio-active lamps," at first for physical and chemical researches,[1] and more recently, in the laboratories of the Harvard Cancer Commission, for use in methods he has devised for investigating the therapeutic value of radio-activity in the treatment of cancers. The construction of these powerful sources of radiation requires the extraction of radium emanation from a great many milligrams of radium, its purification and its compression into small volumes. As many requests have been received for a description of the method employed, it does not seem out of place to publish the details of the apparatus.

The general principles of the method are those previously employed by Ramsay and Soddy, Rutherford, and Debierne,[2] in some of their most important researches. The advantages of the method described below are: that the purification does not require liquid air; that a large number of millicuries of emanation can be purified and compressed into a small fraction of a cubic millimeter, in ten or fifteen minutes of time; that no emanation is lost except that due to its natural decay; and that the process may be repeated a great many times without renewing parts of the apparatus.

Fig. 1 represents the arrangement of the glass tubes and reservoirs. The bulb *A* contains the radium salt dissolved in water. Radium in solution continually decomposes the water into hydrogen and oxygen, and at the same time transforms itself into the emanation, which is set free. The total volume of the hydrogen and oxygen amounts to more than

[1] Comptes rendus, *153*, p. 336, July 31, 1911.

[2] For a brief description with references see Madam Curie, Traité de Radioactivité, Tome I., pp. 312–322.

two hundred thousand times that of the emanation at the same pressure and temperature.[1] In addition to the oxygen and hydrogen and emanation, a small quantity of helium appears (the volume of which is a few per cent. greater than that of the emanation) and also traces of other gases, probably carbon dioxide and hydrocarbons coming from the decomposition of organic impurities, although the source of these traces of gas does not seem to be thoroughly understood. On account of its radioactive transformation, the exact proportion between the quantity of emanation and the gases with which it is mixed, depends upon the length of time the gases are allowed to accumulate. In the ordinary daily routine of our laboratory, however, the problem resolves itself into the extraction of 35 to 60 millicuries of emanation having a volume of 0.021–0.036 mm³. at atmospheric pressure and ordinary temperature, from a mixture of gases, having a volume of 4.5 to 9 c.c. at the same temperature and pressure.

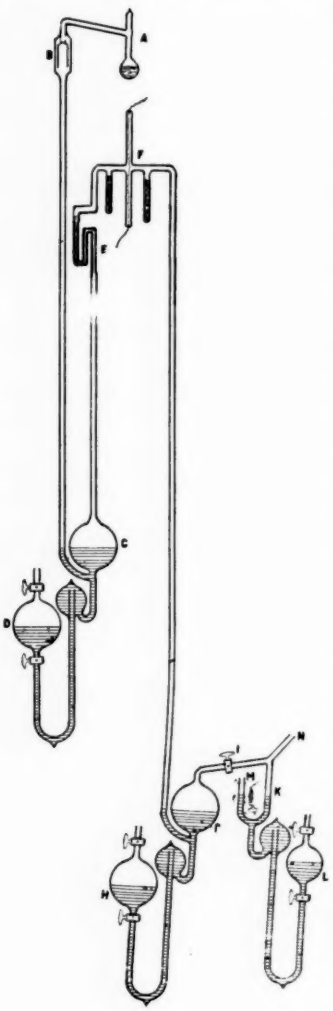

Fig. 1.

The mixture of gases collects in *A* and the tube *B*, and also, if the passage is open, in the reservoir *C*. Allowing the gases to collect in *C* apparently increases the efficiency, probably because the emanation defuses from the solution into a large volume more freely than into a small one. The tube *B* is considerably longer than 76 cm. so that air may be admitted into *C*, if desired, without its finding its way up to the radium solution. The trap at *B* protects against mercury spurting up into the radium solution, should some of the glass apparatus break. An ordinary water aspirator with suitable stop-cocks controls the flow of mercury between the reservoirs *C* and *D*. On admitting the air into *D*, the mercury rises in *C*, pushing the mixture of gases through the mercury trap *E*, into the tubes *F*. The mercury in the trap *E* holds back all but

[1] Duane and Scheuer, Le radium, *10*, p. 33, 1913.

a very small quantity of the water vapor. The tubes *F* contain a copper wire slightly oxidized, phosphorpentoxide and potassium hydroxide. Although represented in the figure in a vertical position, the copper wire really lies horizontal. It is wound on a hard glass rod supported by glass feet, so that the wire does not touch the inner surface of the tube at any point. The diameter of the wire is 0.3 mm. and the length of the coil 25 cm. When heated red hot by an electric current of 5–10 amperes it rapidly combines the oxygen and hydrogen, the phosphorpentoxide absorbing the water vapor formed. A small amount of copper oxide on the wire is required, because the mixture of gases contains, at least at first, a quantity of hydrogen that exceeds by a few per cent. the proportion required by the chemical formula for water. Some oxygen remains in the radium solution as hydrogen peroxide. The copper wire was heated for a long time to remove as much of the occluded gases as possible, and the phosphorpentoxide was distilled into its present position from a tube sealed on just below it, and afterwards removed; both of these processes taking place in vacuum. The potassium hydroxide is for the purpose of absorbing any carbon dioxide that may be present, or may be formed by the hot copper wire oxidizing hydrocarbon gases.

After the purification of the emanation the mercury in the reservoir *G* is drawn into *H*, the air being removed from *H* by the water aspirator, and the emanation and helium pass into *G*. The gases are then pushed up by the mercury through the stop-cock *I* and into the desired tube or container, which is sealed on at *N*. The volume of the helium being very small, for the vast majority of purposes it is unnecessary to remove it. The length of the tube connecting *E* with *G* should be so great that air may be admitted into *G* without forcing the mercury up into *F*.

The stop-cock *I* has a mercury seal, and contains no stop-cock grease. A few marks made with a lead pencil on the stopper allow it to turn freely. It will be noticed that the emanation passes through no stop-cock except the one at *I*, and even this is unnecessary, and has been added for convenience of manipulation only. The fact that stop-cock grease and many other organic substances are decomposed by the rays from the emanation and give off gases is well known.

The system of tubes and bulbs *K*, *L*, *M* is for the purpose of removing the air from the other tubes and reservoirs, etc., by means of a pump attached at *M*. This must be done at the beginning, and after that no air enters the reservoirs except occasionally when it becomes necessary to renew the oxidized copper wire or the phosphorpentoxide, etc.

The apparatus in our laboratory has been in continuous daily use for more than eighteen months. The bulb *A* contains over two hundred and

twenty milligrams of radium (element), and the total quantity of emanation purified per month amounts to slightly more than one curie of emanation, which is the quantity of emanation in equilibrium with one gram of radium (element).

Fig. 2 represents a few of the tubes and applicators used in investigating the effects produced by the Becquerel rays on cancers. The tiny glass tubes *A* contain radium emanation. They fit into the steel tubes just below them, which are provided with eyes and points as shown. While strongly active these tubes are used singly either with or without the silver jackets represented at *B*. The silver jackets act as filters, cutting off the easily absorbed rays. As the emanation disappears and the tubes become less active, a lot of them are placed together on flat applicators as at *C*. Thus each individual tube remains in use for over a month, at the expiration of which time the activity has fallen to less than one half per cent. of its initial value. *D* is a glass tube containing a thin sheet of metal. It illustrates the method of making deposited activity applicators, two of which are represented at *E*.

The glass bulbs *F* have been used to make highly radio-active solutions. The small bulb having been filled with common salt the tube is sealed on to the apparatus at *N*, Fig. 1, and the purified emanation is pushed up between the grains of salt, on which it deposits radium *AB* and *C*. On dissolving the salt in a small quantity of water a very active solution of deposited activity is obtained.

The advantages of using the emanation and deposited activity instead of the radium itself appear to be, (*a*) that the danger of losing the radium is reduced to a minimum, (*b*) that great flexibility as to the size, shape and strength of applicators, and penetration of rays may be obtained, and (*c*) that no large quantity of a radio-active substance of long life, such as radium, can become lodged by accident in the patient's body.

HARVARD UNIVERSITY.

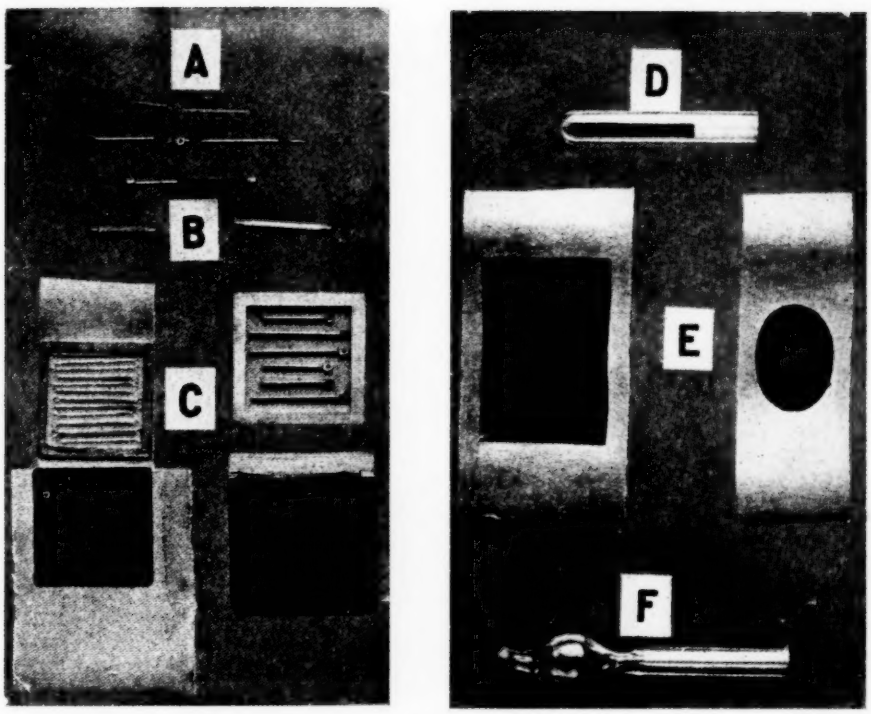

Fig. 2.

THE NATURE OF THE ULTIMATE MAGNETIC PARTICLE.

BY K. T. COMPTON AND E. A. TROUSDALE.

Introduction.—For many years scientists have agreed in ascribing the magnetic properties of bodies to the action of exceedingly small elementary magnets, but the nature of these ultimate magnetic particles has remained an open question. This theory in its earliest form was due to Weber, who supposed that the molecules of substances are magnetic doublets whose axes are arranged at random in the unmagnetized substance but, in opposition to restoring forces of elastic nature, are so directed by an external field that the substance acquires a definite resultant magnetic moment. Wiedemann suggested that the opposing couples are of a frictional nature, thus accounting for hysteresis but failing to explain magnetization in very weak external fields. Ewing then suggested that the only restraints on the molecules are due to the mutual magnetic forces occurring between neighboring molecules and showed that the residual magnetism and hysteresis of ferromagnetic substances may be thus accounted for. None of these theories accounted for diamagnetism. A development of Weber's theory, due to Ampère, is that the magnetic properties of molecules are caused by electric currents circulating about perfectly conducting circuits within the molecules. Maxwell showed that, when placed in an external magnetic field, the induced currents set up in these molecules would tend to oppose the field and thus give to the substance diamagnetic properties, while the change in the orientation of the molecular circuits would give rise to paramagnetic properties. Thus a substance is dia- or para-magnetic according as the former or the latter effect predominates.

With suitable modifications, Ampère's theory of molecular currents has been made the basis of the electron theory of magnetism, whose development is due largely to Langevin and Weiss. On this theory electrons revolving in orbits around the atomic nucleus give rise to magnetic fields and constitute the ultimate magnetic particles. In the presence of an external field the magnetic moments of the electron orbits are diminished in the direction of the external field by an effect analogous to electromagnetic induction, so that the resultant effect is of a diamagnetic nature. If the resultant magnetic moment of the electron

orbits in each atom be different than zero, the planes of the orbits will be oriented so that the magnetic axis of each atom will tend to point in the direction of the external field. This gives rise to paramagnetism, whose intensity depends on the strength of the external field, the magnitude of the resultant magnetic moments of the atoms, the interatomic forces of electrostatic or other nature and the demagnetizing effect of the kinetic reactions due to thermal agitation. Ferromagnetic substances are those in which the resultant magnetic moments of the atoms are so large that all other interatomic forces are negligible in comparison.

A recent theory[1] suggests that certain numerical relations are most readily explained on the assumption that the ultimate magnetic particle is a natural unit, called the magneton. At present this must be regarded as a mere hypothesis, with a possible basis of fact, since its usefulness in explaining magnetic phenomena is limited to a very small number of phenomena.

The electron theory has been generally accepted as offering the most reasonable explanation of magnetic phenomena and is strongly supported by its success in accounting for the Zeeman effect. Yet there are several magnetic phenomena which apparently receive the readiest explanation on the molecular theory. The most significant of these are: (*a*) The influence of temperature, a molecular effect, on the magnetic properties of substances; (*b*) the effect of a changing magnetic field on the temperature, *i. e.*, on the average kinetic energy of the molecules of substances; (*c*) the effect of chemical combination, as in the case of iron salts and Heusler alloys; (*d*) the effect of mechanical jarring on the ease with which certain substances may be magnetized.

The recently developed method of determining the positions of atoms within a crystal by X-ray photography and the ferro-magnetic properties of magnetite, hematite and pyrrhotite crystals suggested a direct experimental method of eliminating one or the other of these theories. The magnetic properties of these crystals have been investigated by Weiss,[2] who found that these crystals may be magnetized strongly in the direction of each crystal axis, but that the degree and ease of magnetization is different along different axes. It is practically certain that the magnetic properties of iron and other substances are determined by the properties of the agglomeration of minute crystals of which they are composed. Thus the magnetic properties of crystals are typical of those of all magnetic substances.

We accordingly passed a beam of X-rays through crystals and obtained

[1] Weiss, Le Radium, Vol. 8, p. 301, 1911.

[2] Journal de Physique, *3*, 5, p. 435, 1896; *4*, 4, p. 469, 1905.

on photographic plates the diffraction patterns which were determined by the arrangements of the atoms within the crystals. By comparing the photographs taken through the unmagnetized crystals with those taken through the same crystals when magnetized to various intensities it was possible to determine with certainty whether or not the atoms of a substance experience a translational displacement in the process of magnetization. We have found that no such motion occurs and hence that the molecular theory of magnetism, at least in its ordinary form, is untenable.

Apparatus and Method.—A powerful self-regulating X-ray bulb was enclosed in a lead box *EF* in such a position that a pencil *ab* of X-rays passed out through an opening *H*, through pin holes in the lead shields *LL'*, through the crystal *C* to the photographic plate *P*. The crystal was cemented by " Quixo " cement to one of the adjustable pole pieces *S* of an electromagnet capable of setting up a field of 1,000 gauss in the air gap. The other pole piece was prevented from touching the crystal in order to obviate the danger of a mechanical displacement of the crystal when strongly magnetized. The apparatus was enclosed in the light

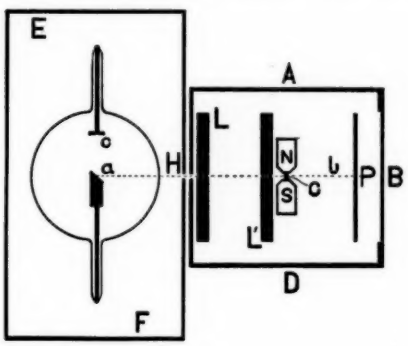

Fig. 1.

tight box *AD* with a removable back *B*. This box was made of sheet iron in order to reduce the effect of the magnetic field on the path of the cathode rays from *c* to *a*. Cramer X-ray plates, " New Process," were used, and the negatives were later intensified. The distance of the plate from the crystal was three inches and the exposures were for three hours.

The procedure was to take a photograph through the unmagnetized crystal, then, without disturbing the crystal, turn on the current in the electromagnet and take a second photograph with the crystal magnetized, then take a third photograph with the direction of the magnetic field reversed and finally take another photograph with the crystal unmagnetized. This last photograph was a check to guard against possible effects

due to any change in the position of the crystal. Supplementary experiments showed us that in every case the magnetic fields were of sufficient strength to strongly magnetize the crystal.

In this way a number of series of photographs were taken through crystals of magnetite and hematite variously oriented with respect to the magnetic field. In no case did we discover that magnetization influenced the diffraction pattern.

Two of these series of photographs, one taken with magnetite M and the other with hematite H, are shown in the accompanying figure. (a), (b), (c), (d) refer to the cases of the unmagnetized, magnetized, reversely magnetized and unmagnetized crystals. Unfortunately in bringing out the spots more clearly by intensifying the plates we did not succeed in strengthening the spots equally on the four plates. In the original negatives there was no difference in the cases (a), (b), (c), (d) either in the relative intensities or the positions of the spots. The "fogging" of several of the pictures is also due to the intensifier. We have not as yet succeeded in obtaining specimens of pyrrhotite crystals.

Discussion of Results.—These results show conclusively that the ultimate magnetic particles must be atoms or something within the atoms and are therefore consistent with the electron theory of magnetism. Doubtless a change in the orientation of an atom means the same thing as a change in the orientation of an electron orbit within the atom, since a turning of an electron orbit would upset the equilibrium of the remaining constituents of the atom so that the whole atom would change its orientation. However this may be, it is certain that the ultimate magnetic particle cannot be a molecule or other group of atoms, since the turning of such a system would involve a translational motion of atoms, which the present investigation shows does not exist.

PHYSICAL LABORATORY,
REED COLLEGE.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

LUMINESCENCE.[1]

BY ERNEST MERRITT.

THE past twenty years have been remarkable in the history of physics on account of the large number of fundamental discoveries that have been made, each of which has opened up an entirely new field of investigation, and each of which has exerted a profound influence on the trend of speculation. I refer particularly to the discovery of X-rays and its modern development in the high frequency spectra, the discovery of the electron, and of radioactivity. But many other subjects of scarcely less importance might be included in the list; such, for example, as the photoelectric effect; and, on the theoretical side, the hypothesis of quanta. In each of these cases the original discovery not only appealed to physicists at once on account of its obvious importance, but possessed also the charm of complete unexpectedness. And in each case the subsequent development of the new subject was so rapid as to be almost spectacular.

In looking over the ground from our present point of advantage it is interesting to observe how these different subjects have supplemented one another, and how in some subconscious way we have been proceeding by seemingly accidental steps toward a definite goal,—toward the solution of the problem of the structure of the atom, which is now so generally recognized as the most important of the outstanding problems of our science.

On account of its important bearing upon this problem of atomic structure the subject of luminescence, in my opinion, deserves a place in the group of subjects just mentioned. In some respects, in fact, it offers a more direct line of attack than any of these. The chief purpose of my address to-day is, therefore, to make a plea for the more extended study of the phenomena and the theory of luminescence.

Luminescence is not a new subject. It cannot attract investigators by its novelty. If none of its phenomena were known, and if the phosphorescence of Sidot blende or the fluorescence of anthracene were to be shown at this

[1] Presidential address delivered at the Philadelphia meeting of the Physical Society, December 29, 1914.

meeting for the first time, I am confident that half of this audience would be investigating luminescence within a week. But the first discovery was made three hundred years ago. The fascinating phenomena of luminescence have to a large extent lost the appeal of novelty, for in a superficial sort of way they are well known; but so far as the theoretical interpretation of the phenomena is concerned we have made only the barest beginning. The original discovery was made too soon—before the scientific world was ready for it. Important progress has indeed been made, especially on the experimental side; but it has been made slowly and with great effort. Until very recently the position of the subject has been like that of an isolated outpost of an army: it lacked support on the two wings. But the great advance of Physics during the past twenty years has at last furnished the much needed support, and it seems to me that the time has come for the outpost to advance.

Having in mind the general question of the bearing of the phenomena of luminescence upon the problem of atomic and molecular structure, the various subdivisions of our subject may be roughly grouped in two classes. The first class includes such subjects as phosphorescence, chemiluminescence, and the influence of temperature upon these phenomena. The interpretation of the phenomena of this class involves a consideration of the relations between molecules, but does not necessarily require any hypothesis regarding the mechanism by which the light is actually emitted. We have a somewhat analogous case in the subject of magnetism, where important progress was made by the assumption that each molecule is a magnet, even before any serious attempt was made to explain the peculiarities of molecular structure to which the assumed magnetic property was due.

The second class of subjects, which bears more directly upon the problem of atomic structure, includes such matters as the detailed study of luminescence spectra, the relations between luminescence and absorption, and the influence of the wave-length of the exciting light, or more generally the influence of the mode of excitation, upon the character of the light emitted. No progress toward a theoretical interpretation is possible in these cases without some hypothesis regarding the mechanism of emission and absorption. I need hardly point out that it is often difficult, if not impossible, to entirely separate the two classes of problems.

As an illustration of important progress made by purely empirical experimentation, without the help of even the crudest theory, we have the development of the methods now used in preparing phosphorescent materials artificially. In the early days the results of attempts to make phosphorescent materials were very uncertain. Preparations made by the same method and from the same materials were in some cases brilliantly phosphorescent and in other cases entirely inactive. The color of the phosphorescence and its duration also seemed to be largely a matter of chance. An important step toward an understanding of the reasons for these uncertainties was taken by Lecoq,[1]

[1] See Kayser, Handbuch der Spectroscopie, Vol. IV., p. 741. The chapters on Phosphorescence and Fluorescence in Kayser's Handbuch contain so complete and valuable a

who was led to believe that in most cases phosphorescence was due to the presence of impurities. Thus $CaSO_4$ gives very weak phosphorescence and $MnSO_4$ none. But if we mix the two we get a mixture which is brilliantly phosphorescent. Lecoq was the first also to suggest that phosphorescent substances were to be looked upon as solid solutions, a view which is now very generally accepted. Thus Sidot blende consists of a small amount of copper or manganese dissolved in zinc sulphide. Balmain's paint is a solid solution of bismuth in calcium sulphide. The usual method of preparation is by the calcination of the mixed dry salts.

Lecoq's views were confirmed by Verneuil, who found that better results were obtained if a flux such as NaCl or Na_2CO_3 was used. More recently Lenard and Klatt have developed the procedure in the case of the metallic sulphides in great detail, so that if we have pure materials to start with we are now in a position to reproduce the phosphorescent preparations of this class with considerable certainty.

Wiedemann and Schmidt have used two other methods of preparation, which, while probably not so generally applicable, sometimes have the advantage of not requiring calcination. One of these methods simply calls for the evaporation to dryness of a suitable mixture of two salts. For example, if a small amount of a solution of $MnCl_2$ is added to a solution of NaCl and the mixture evaporated to dryness, the dry salt gives a pink phosphorescence.[1] In some cases the precipitation of a metal from a solution will carry down a sufficiently large amount of some other metal present to give the proper conditions for phosphorescence in the dried precipitate.

In all these cases the essential thing seems to be the bringing into intimate association of a small amount of one substance—usually called the active substance—and a large amount of some other substance, the latter acting as the solvent in the resulting solid solution. The intensity of phosphorescence is found to vary greatly with the concentration, increasing rapidly with the concentration at first and, after reaching a sharply defined maximum, decreasing scarcely less rapidly as the amount of active material is still further increased. In the case of the solid solution of $MgCl_2$ cited above the maximum is reached for a concentration of 0.8 per cent. The sulphides studied by Lenard and Klatt usually give maximum brightness with a concentration of .01 per cent. or less.

In cases where so small an amount of active substance is required for brilliant results it is evident that the purity of the materials used is a matter of great importance. It is very difficult to obtain a salt which is sufficiently pure to be entirely free from phosphorescence, especially when tested by cathode rays. The extreme sensitiveness of certain substances to small traces of impurity is illustrated by an experience described by Waggoner.[1] After a long search

discussion of the literature down to the date of publication (1908) that I have usually not thought it necessary to cite references except in the case of work done since that date.

[1] C. W. Waggoner, PHYS. REV., XXVII., p. 209.

some cadmium sulphate had been obtained which showed only the barest trace of afterglow. This was dissolved in water that had been twice distilled, but which had stood in a glass bottle over night. When the solution was evaporated to dryness the salt was found to be brilliantly phosphorescent. The water had evidently dissolved some substance from the glass of the bottle in which it had been kept. But when 200 c.c. of the water from the same bottle was evaporated in a platinum vessel it left a residue so small that it could be seen only when the vessel was at a red heat. There are many evidences that phosphorescence may often give a test of purity which is equalled in sensitiveness only by spectroscopic examination, or by the ionization test for radium.

That luminescence in minerals is also due to impurities has been definitely proved in a large number of cases. Probably we all recall the important assistance that was given by kathodo-luminescence in the study, and in some instances the discovery, of several of the rare earths. The opinion is now generally held that impurities are present in the great majority of cases of luminescence in solids, possibly in all cases. Yet there does seem to be one exception, namely the salts of uranium. The presence of slight impurities in these salts is of course probable. But their fluorescence seems to be chiefly determined by the uranyl radical, and retains the same general character whatever may be the acid with which this radical is combined or the source of the uranium. This exception to the general rule is so striking that I have sometimes wondered whether the active substance in this case may not be one of the radio-active products of uranium, for which the salt serves as a solvent. A few experiments have been made to test this conjecture. For example the salt has been freed from Ur-X in the hope that it would lose its fluorescence thereby until new Ur-X was formed. But the results are thus far altogether negative.

On the whole very satisfactory progress has been made in developing methods of preparing phosphorescent materials. And yet we can scarcely feel content, for the knowledge gained is almost entirely empirical. We have no means of telling what substances may be used to advantage either as solvents or as active substances—except, of course, that certain materials have been tried before and have been found to work. The fact that phosphorescent substances are in most cases solid solutions is virtually the only generalization that can be used as a guide.

In some of the other problems of luminescence the situation is better, for a suggestion first made by Wiedemann in 1889 and since resuggested in more or less modified form by several other physicists, has proved of great utility. According to the Wiedemann theory luminescence is an accompaniment of what the chemists would call, I believe, a reversible reaction. It is assumed that the active substance is changed by the action of the exciting agency from the stable condition A into the unstable condition B. If the return of the substance to the condition A is accompanied by the emission of light we have phosphorescence. Fluorescence may be due either to vibrations set up during the change from A to B, or to the fact that the reaction B to A proceeds, with

the emission of light, during excitation as well as during decay. We should expect, therefore, that the fluorescent light, that is the light emitted during excitation, would consist in part of the same wave-lengths that are present during phosphorescence, but that other wave-lengths, resulting from the reaction A to B, may also be present and in some cases predominant. An explanation is thus offered of the fact that the color of phosphorescence is often different from that of the fluorescence of the same substance with the same excitation. Thermo-luminescence is to be explained as the result of some change that is made possible by rise of temperature, during the progress of which the molecules are thrown into such violent vibrations as to emit light. In many instances thermo-luminescence seems to be nothing more than accelerated phosphorescence. In such cases the conditions at the temperature of excitation are apparently not favorable for the rapid emission of the energy stored during excitation. Phosphorescence is therefore very weak and of extremely long duration. This may be true in so marked degree that no phosphorescence can be detected at all, and the condition produced by excitation is practically permanent so long as the physical conditions remain the same. In such cases the reaction A to B can occur at the lower temperature, while the reverse reaction B to A cannot. But if the temperature is raised it becomes possible for the stored energy to be liberated and thermo-luminescence is observed. In such cases the material will not show thermo-luminescence when heated a second time until it has been reexcited, say by the light of a spark or by cathode bombardment. If all cases of thermo-luminescence are of this kind we should not expect thermo-luminescence to be shown unless there has at some time been an opportunity for excitation. In the case of certain natural minerals whose freshly exposed surfaces were found to show thermo-luminescence even when the specimen had been broken in the dark, it has been suggested that the original excitation was due to radium rays.

The theory illustrated by these few examples was first advanced by Wiedemann in his well known paper entitled "Zur Mechanik des Leuchtens."[1] It was discussed in much greater detail in a later paper by Wiedemann and Schmidt,[2] which appeared in 1895, and which in my opinion is to be regarded as one of the classics in the field of luminescence.

While the fundamental conception of the Wiedemann theory has been retained, it has been customary in recent years to make the hypothesis more definite by assuming that the change which I have referred to as the reaction A to B consists in the expulsion of an electron from a molecule of the active substance, while the recombination of the ions thus formed constitutes the reverse reaction B to A. This is the form of the theory that has been advocated by Stark, Lenard and others. Chemists I believe are still inclined to look upon the change assumed in the Wiedemann theory as a chemical reaction in the ordinary sense. My own feeling is that we must admit the existence of several distinct types of luminescence, in some of which the phenomena are

[1] E. Wiedemann, Annalen der Physik, 37, p. 177, 1889.

[2] E. Wiedemann and C. C. Schmidt, Annalen der Physik, 56, p. 177, 1895.

explainable in terms of electron dissociation alone, while in others chemical changes form the predominant factor. Although it may later be possible to bring all cases of luminescence into one category as regards the process which leads to the emission of light, I doubt whether we are yet in a position to do this.

In support of the Wiedemann theory in its general form we have several well established facts. For example when fluorescence is excited in liquids or in isotropic solids the light emitted is unpolarized, regardless of the condition, as regards polarization, of the exciting light. Apparent exceptions are noticed when the fluorescent surface is observed at an oblique angle, since the light from the interior is partially polarized by refraction when it passes into the air. But a study of such cases by Millikan has shown that there is nothing to indicate any polarization in the light before it reaches the refracting surface. The absence of polarization is one of the strongest arguments against any theory which assumes that the vibrations causing emission are set up by some process analogous to resonance. On the other hand it is just what we should expect from the Wiedemann theory, since the light emitted during the change B to A cannot be affected by the manner in which the condition B was established. The argument is equally strong whether the process B to A consists in the recombination of ions or in a chemical reaction. In the case of the fluorescence of vapors, Wood has found that the fluorescence light is partially polarized.[1] This fact offers support to the view that the processes of excitation and emission are essentially different from the corresponding processes in solids and liquids, and justifies the term resonance radiation which Wood has applied to this type of fluorescence.

Experiments made with excitation by light of different wave-lengths, by X-rays, and by cathode bombardment indicate that the distribution of energy in a fluorescence spectrum is the same for all of these modes of excitation.[2] It often happens that not all of these exciting agencies are effective; or that the substance tested possesses several independent fluorescence bands, which are excited by the different agencies to a different extent. In such cases the color of the total light emitted may vary with the mode of excitation. But if we direct our attention to some one band it is found that if this band is excited at all the distribution of intensity throughout the band is the same for all modes of excitation thus far tested. This result is of course what the Wiedemann theory would lead us to expect, for the phenomena connected with the change from the condition B to the condition A will not depend upon the means by which the change from A to B was produced. Or, speaking in terms of the modern form of the theory, the effects produced when an electron reunites with the positive nucleus will be the same no matter what method was used in bringing about its dissociation.

Similar reasoning based on the Wiedemann theory would lead us to expect that the distribution of energy in a phosphorescence band will remain the same throughout the period of decay. On account of the faintness of phosphores-

[1] R. W. Wood, Philosophical Magazine, 26, p. 846, 1913.

[2] E. L. Nichols and E. Merritt, PHYS. REV., XXVIII., p. 349.

cence spectra this conclusion is difficult to test with any high degree of accuracy; but in so far as it has been possible to test it the conclusion is confirmed.[1]

Studies of the law of decay of phosphorescence, while leading in many cases to confusing and even contradictory results, on the whole lend support to the Wiedemann theory. If the exciting light produces a separation of the active material into two parts—and if this is its only effect—then we should expect the recombination to occur in accordance with the laws that apply to bimolecular reactions. It can readily be shown that in this case the law of decay should be

$$I = 1/(a + bt)^2 \quad \text{or} \quad 1/\sqrt{I} = a + bt$$

where I is the intensity of phosphorescence at any time t.[2] The law can be conveniently tested by plotting the reciprocal of the square root of I against t, in which case, if the law is obeyed, a straight line is obtained.

In the case of the afterglow in gases Trowbridge has found this law to hold with great exactness.[3] It also applied during the early stages of decay in the case of a number of solids, for example in the case of Sidot blende. Usually, however, when $I^{-1/2}$ is plotted against t the resulting curve is found to consist of two parts, each of which is nearly straight, separated by a region of rather sharp curvature.[4] Such curves suggest that the decay involves two processes, which have been called by Lenard the Momentan-prozess and the Dauer-prozess, the former being predominant during the early stages of decay and the latter during the period of slow decay which follows. In Lenard's experiments the first or Momentan-prozess has been found to follow a law of the exponential type.

Ives and Luckiesch[5] have found that in some cases even the second process does not give a linear relation, but shows considerable curvature, sometimes curving up and sometimes down.

The question of the decay of phosphorescence is complicated by two considerations, both of which are neglected in the derivation of the simple linear law. In the first place phosphorescent solids are very far from being homogeneous, and it has been shown that lack of homogeneity is in itself sufficient to account for most of the observed deviations from the simple law.[6] In the second place we have no reason to feel sure that a separation of the active material into two parts is the only effect of excitation. Secondary changes, possibly chemical in their nature, may in many cases follow this primary change. Both of these disturbing factors may perhaps be removed by working at low temperatures.

[1] E. L. Nichols and E. Merritt, PHYS. REV., XXI., p. 247, 1905; C. W. Waggoner, PHYS. REV., XXVII., p. 220; C. A. Pierce, PHYS. REV., XXX., p. 663, XXXII., p. 115; H. E. Ives and M. Luckiesch, Astrophysical Journal, XXXIV., Oct., 1911.

[2] E. L. Nichols and E. Merritt, PHYS. REV., XXII., p. 279, 1906.

[3] C. C. Trowbridge, PHYS. REV., XXVI., p. 515; XXXII., p. 129.

[4] E. L. Nichols and E. Merritt, Carnegie Publication, No. 152.

[5] H. E. Ives and M. Luckiesh, Astrophysical Journal, Vol. XXXVI., p. 330, 1912.

[6] E. L. Nichols and E. Merritt, Carnegie Publication, No. 152, Chapter XV.

At the temperature of liquid air secondary chemical changes could scarcely occur. While if an amorphous phosphorescent substance is formed by freezing a homogeneous solution we should expect that the material would be approximately homogeneous. Experiments along this line by Kennard[1] are encouraging, since in the case of paraffin and frozen kerosene the decay, at the temperature of liquid air, was found to follow the linear law.

The study of phosphorescence is also complicated by the fact that in many substances the effect produced by a given excitation is largely affected by the previous history of the specimen. After a substance has been excited and then allowed to decay until no trace of phosphorescence can be detected its condition is usually not the same as it was originally. If subjected for a second time to the same excitation, even after a rest of several days, its phosphorescence is found to be brighter and of longer duration. In many cases also the substance is found to be thermo-luminescent. In studying the decay of phosphorescence this residual change must be taken account of, and in the more recent work the substance has usually been brought back to a standard condition by heating, or by brief exposure to infra-red radiation. But the cause of the residual change and the methods for its removal are so little understood that we cannot feel at all certain that the disturbances due to it are really eliminated.

Another source of disturbance,—which is at the same time a very interesting phenomenon in itself—is the effect of the red and infra-red rays upon the decay of phosphorescence. In the case of Balmain's paint the longer rays cause a considerable increase in the brightness of phosphorescence, which, however, is only temporary and is followed by more rapid decay. In Sidot blende it has usually been thought that the effect is simply to increase the rapidity of decay without any preliminary increase in brightness. But Ives and Luckiesch[1] have found that while this is true during the early stages of decay, a temporary flashing up of phosphorescence can also be observed in Sidot blende if the exposure to infra-red takes place after the decay has proceeded for several minutes.

It is clear that the phenomena of phosphorescence are extremely complex. And unfortunately the complexity appears to be especially great in the case of the substances that are most common and therefore most frequently studied. The problem has not yet been reduced to its lowest terms. In the further study of the subject it appears to me of the greatest importance to choose the conditions of observation, if this is possible, so as to eliminate some of the sources of disturbance. The work of Kennard[2] at low temperatures appears to be a promising step in this direction.

Let us consider now the problems of luminescence which are more obviously and directly connected with the question of atomic structure. Take for example the question of the relation between the wave-length of the exciting light in the case of fluorescence or phosphorescence and that of the light emitted.

[1] Kennard, E. H., PHYSICAL REVIEW, IV., p. 278, 1914.

[2] Ives and Luckiesch, Astrophysical Journal, Vol. XXXIV., p. 173, 1911.

[3] Kennard, E. H., PHYSICAL REVIEW, IV., p. 278, 1914.

Since excitation cannot occur without absorption this question is closely connected with that of the relation between the luminescence spectrum of a substance and its absorption spectrum.

The law, first enunciated by Stokes, that the wave-length of the fluorescent light is always longer than that of the exciting light has led to extended discussion and experiment. Probably more papers have been published dealing with Stokes' law than on any other topic connected with luminescence. The fact that there are many cases where the law is violated seems to be now well established. The most striking exceptions to the law are probably those found by Wood in the case of fluorescent vapors. But even in these cases the longest wave-length that will excite luminescence is only a little longer than the shortest wave-length in the light emitted. As a general statement of what appears to be a fundamental relation the law still retains its value.

For a long time Stokes' law was thought to be exact, and attempts were made to base it upon thermodynamic reasoning. Fluorescence was thought of as a case of degradation of energy, the transformation of the short wave energy of the exciting light into the long wave energy of fluorescence being looked upon as somewhat analogous to the passage of heat from higher to lower temperature. I think that the attempts to base Stokes' Law on the Second Law of Thermodynamics are now generally regarded as unsound. Nevertheless this view has many attractive features, and it does not seem to me that it should be finally dismissed until, with the aid of the more recent methods of thermodynamics, it has been again considered.

Another explanation of Stokes' law has been based upon the theory of quanta. If excitation is due to the emission of electrons under the influence of the exciting light, in other words to a process analogous to that of the ordinary photoelectric effect—the velocity with which the electron leaves the active molecule will be determined by the wave-length of the exciting light. Similarly the wave-length of the light emitted when the electron returns will be determined by its energy at the time of recombination. Owing to collision with other molecules, however, a portion of the energy of the electron will generally be lost before an opportunity for recombination occurs. On the whole, therefore, the frequency of the light emitted will be less than that of the exciting light. This explanation has the advantage of accounting for the deviations from Stokes' law, for there will always be some electrons, although relatively a small number, which gain energy by collision before returning, and the light emitted during recombination will in such cases have a shorter wave-length than the exciting light. This view leads us to expect also that the deviations from Stokes' law will be less marked at low temperatures; and the small number of experiments which bear upon this question are in agreement with the theory. This explanation of Stokes' law, which is due to Einstein, is interesting in being almost the only case in which the theory of quanta has been applied to luminescence.

In the case of solids and liquids the fluorescence spectrum usually consists of one or more bands, shaded in both directions from a well defined maximum,

and rarely less than one or two hundred Ångström units in width. In some cases the band may extend nearly throughout the visible region. In a large class of cases, but apparently not in all, the region of most intense excitation is immediately adjacent to the fluorescence band, on the short wave side. This region of excitation corresponds, of course, to a region of absorption; and in a large class of substances, of which fluorescein and eosin are typical, a certain symmetry is noticeable when we compare the curve of intensity in the fluorescence spectrum with the curve which gives the absorption coefficient as a function of wave-length. The fluorescence curve is steep on the short wave side and dies away gradually toward the red; while the absorption curve is steep on the long wave side and dies away gradually toward the violet. In cases where the two curves overlap, and this is usually the case, Stokes' law is violated.

Although the region of maximum excitation occupies the position just described, the substance is usually excited to some extent also by light of shorter wave-lengths. This fact is very beautifully illustrated by throwing a spectrum from a quartz prism upon the surface of a solution of one of the fluorescent dyes, such as fluorescein. The brightness of the fluorescence excited by the relatively weak ultra-violet rays is often such as to suggest that the energy of the light is more efficiently utilized for excitation when in the form of short waves. There has been no experimental test of this conjecture in the case of ultra-violet excitation. But throughout the principal absorption band the reverse has been found to be true.[1] The specific exciting power, that is the fluorescence excited by a given amount of absorbed energy, is greater for light at the long wave side of the band than in the middle, and still greater than for light on the violet side. I am inclined to think that we have here a promising case for the application of the theory of quanta, which by the aid of plausible hypotheses may be made to give at least a qualitative explanation of the facts.

While most substances possess a luminescence spectrum in which the bands are few in number and quite broad there are several exceptions, and the number of exceptions is increasing as the study of luminescence proceeds. In the case of anthracene there are four or five bands, which are narrow even at ordinary temperatures and become quite narrow as the temperature is lowered. A still more notable case is that furnished by the uranium salts, which have played so important a part in the history of luminescence as well as in the history of radioactivity.

The fluorescence of these salts is not only remarkable because of its brilliancy, but still more so on account of the structure of its spectrum, the manner in which the energy is distributed among the different bands, and the striking and significant relation that is found to exist between fluorescence and absorption. Brilliant fluorescence is shown only in the uranyl salts, *i. e.*, the salts in which the uranium occurs in the radical UO_2. At ordinary temperatures seven or eight bands are usually visible, the width of each being in the neighborhood of 100 Ångström units. Although the different uranyl salts give bands which differ

[1] E. L. Nichols and E. Merritt, Carnegie Publication, No. 152, Chapter XIII.

somewhat in position and width the general appearance of the spectrum is much the same in all cases. The absorption spectrum of these salts also consists of a group of bands, whose width is approximately the same as that of the fluorescence bands. If plotted on the scale of frequencies the bands are found to be spaced at equal intervals, the absorption bands apparently forming a continuation of the bands of fluorescence as we proceed toward the shorter waves. It is found, however, that the regions of fluorescence and of absorption overlap, and that the bands which are common to both regions are "reversible." That is to say these bands will appear as absorption bands if the substance is observed by transmission in white light, but will appear as fluorescence bands if the substance is illuminated by ultra-violet rays only.

If we measure the intensity of the successive bands, starting with the band in the red, we find that the energy increases from band to band until a maximum is reached for a band lying in the green, after which the intensity for each succeeding band is much less than that of the one that precedes it. The distribution of energy in each band as determined by the spectrophotometer is much the same, on a small scale, as the distribution among the bands. Curves plotted to show the distribution of energy in a single band, in the group of bands, in the fluorescence band of a substance like fluorescein, and in the spectrum of a black body, are of the same type, and so strikingly similar in form that we might pass from one to the other simply by changing the wave-length scale.[1] At low temperatures each band of the uranyl spectrum breaks up into a group of lines, and I do not doubt that if the energy distribution in each line could be determined it too would be found to give a curve of the same type. One is reminded by this group of curves of an old rhyme, whose origin I do not recall, but which finds its applications in physics as well as in entomology:

> The very fleas have other fleas,
> And lesser ones, to bite 'em
> And these again have other fleas;
> And so *ad infinitum*.

Upon looking at these curves one can scarcely escape the feeling that both the fluorescence and the absorption regions in a substance like fluorescein are really made up of bands like those in the uranyl salts, but that the bands are so broad as to overlap and form single bands of fluorescence and absorption respectively, which we are unable to resolve.

At the temperature of liquid air both the fluorescence and absorption of the uranyl salts become more complex. Each fluorescence band breaks up into several extremely narrow bands, which are often as sharp as spectral lines; and new lines frequently appear in the regions that were dark at higher temperatures. In the absorption region also the bands are replaced by lines. In general appearance and in complexity these spectra suggest the spectra obtained from an arc or from a vacuum tube. They are in reality, however, much simpler, since it is possible to arrange the lines in groups or series, in

[1] E. L. Nichols and E. Merritt, PHYS. REV., XXXIII., p. 354, 1911.

each of which the lines are spaced at equal intervals on the scale of frequencies. It often happens that the absorption lines can be most satisfactorily arranged in series for which the interval is shorter than that of the fluorescence bands. But in some cases the fluorescence series appear to be continuous with the absorption series, with the interval constant throughout, and with certain lines capable of appearing either as fluorescence or as absorption according to the method of observation.[1]

It is natural to expect that it would be possible, by a suitable choice of the exciting light, to excite one series of fluorescence lines without exciting the rest. As yet, however, no one has succeeded in doing this, although some slight indications have been found that the intensities of the different series do not change in exactly the same ratio as the excitation is changed. Light corresponding to one of the absorption bands is undoubtedly more effective in excitation than that falling in the intervals between bands. But diffuse absorption which is capable of producing excitation is present throughout the short wave region, so that any light lying on the short wave side of the first reversible band is able to excite to some extent. The whole question of the relation between the wave-length of the exciting light and the intensity and structure of the fluorescence spectrum requires further study.

In some respects the most promising field for study in the whole subject of luminescence is that opened up by Wood[2] in his work on the fluorescence or resonance spectra of vapors. Unfortunately the experimental difficulties are so great that few physicists have had the courage to undertake the work. The vapors of sodium, potassium, iodine and many other elements show fluorescence spectra consisting of a vast number of lines, so narrow that these spectra will stand analysis by the most powerful methods of spectroscopy. The absorption spectra of such vapors are equally complex. Wood estimates that the absorption spectrum of iodine contains not less than 35,000 lines in the visible region. The complexity of the phenomena would be altogether disheartening if it were not for the fact that the fluorescence can be greatly simplified by the use of monochromatic light for excitation. If a single line of some strong gaseous spectrum is used for excitation the fluorescence spectrum is found to consist of a relatively small number of regularly spaced lines. At first Wood was of the opinion that each of these fluorescence lines corresponded in position to a line in the absorption spectrum. His more recent work shows, however, that this is not in all cases true.

The lines of a given series, although spaced with great regularity, do not show constant intervals, either on the scale of frequencies or on that of wave-lengths. If plotted to a frequency scale the intervals increase slightly as we pass toward the shorter wave-lengths. In this respect therefore the series are not as simple as the constant interval series of the uranyl salts. It must remembered, however, that Wood has pushed his resolving power much further than would be possible with the uranyl spectra. If the latter could be resolved to the same

[1] H. and J. Becquerel and H. K. Onnes, Leiden Communications, No. 110, 1909.

[2] R. W. Wood, Philosophical Magazine, 24, 673, 1912; 26, p. 828, 1913.

extent and measured with the same accuracy as was reached by Wood in the study of iodine it is not at all unlikely that variations from the constant interval law could be detected.[1]

It will be noticed that there is a striking resemblance between the fluorescence spectra of the uranyl salts when these are observed at low temperatures, and the resonance spectra of vapors,—a resemblance which is the more remarkable when we remember the widely different conditions under which emission occurs in the two cases. In neither case, unfortunately, has experiment gone far enough to make sure that the resemblance is more than superficial. In vapors the resonance bands appear to be closely connected in many cases with the ability of the vapor to rotate the plane of polarization in a magnetic field. In the case of the uranyl salts the magnetic rotation has not been tested. On the other hand in the case of vapors the relation between fluorescence and absorption has not yet been definitely determined so that we are not in a position to say either that the vapors show the same remarkable relation between these phenomena that is so characteristic of the uranyl salts, or that the relation is an entirely different one. To my mind it is a matter of considerable importance to determine whether the phenomena of fluorescence really are essentially the same in these two widely different cases. It has already been pointed out that the ordinary cases of fluorescence like that of eosin may be looked upon as being of the same type as the fluorescence of the uranyl salts, apparently the only difference being that the bands are so broad that they fuse together to form a single band of fluorescence and a single band of absorption. If now it should turn out that the fluorescence of vapors is also of the same type we should be justified in concluding that the fundamental processes involved in fluorescence are the same in all cases.

The study of the fluorescence of rarefied vapors and the study of low temperature fluorescence of solids like the salts of uranyl represent to my mind two attempts, along radically different lines, to simplify the conditions under which emission is caused to occur. In the case of vapors collisions occur only rarely, but when they do occur the disturbing effect upon the process of emission must be of considerable importance. In the low temperature fluorescence of solids each radiating molecule is closely surrounded by other molecules all the time and its vibrations are doubtless in consequence greatly modified. But on the other hand the molecular movements due to temperature are relatively sluggish; and collisions between molecules are far less violent than at higher temperatures; possibly at sufficiently low temperatures, especially in crystals, the molecular movements are reduced to vibrations about a position of equilibrium, with no collisions at all. The experimenter has his choice between a molecule which is

[1] In the measurements of H. and J. Becquerel and H. K. Onnes (Leiden Communications, No. 110, 1909) there is some indication of an increasing interval as we pass toward higher frequencies. In some cases successive intervals differed by as much as 0.1 per cent. In the resonance spectra of sodium each interval is on the average about 2 per cent. greater than the preceding and in iodine 5 per cent.

subjected to large but nearly constant disturbing forces and one which, while ideally free from disturbance most of the time, is obliged to pay for this immunity by occasional periods of extremely great disturbance. I must confess that my preference is for the slow and plodding molecule, in spite of the fact that he is usually found in a crowd. It may be, however, that it will prove possible to combine the advantages of the two methods. If resonance radiation should be discovered in hydrogen or helium for example, or even in oxygen or nitrogen, these gases might be studied in rarefied form at low temperatures, and almost all sources of disturbance would be removed.

It is through the further study of the line spectra of luminescence, of which the resonance spectra of the vapors and the fluorescence spectra of the uranyl salts are typical examples, that I think we may expect the subject of luminescence to contribute most directly to the solution of the problem of atomic structure. Personally I feel that such study offers a more promising line of attack than any other that is now open to us, not excepting even the study of radioactivity or of the X-ray spectra.

Of course I cannot expect this view to be accepted without challenge. In the early days of spectroscopy there was a very general belief that the study of line spectra would enable us to determine the mechanism of emission, and therefore the structure of the radiating atom, in much the same way that we might hope to determine the nature of a sounding body from a study of the relations among its overtones. But the results have been disappointing, and physicists are not nearly so optimistic as they were. Now the subject of luminescence, in so far as it concerns itself with the study of luminescence spectra, is merely a branch of spectroscopy. In fact, if we use the term luminescence in its broadest sense, the greater part of the whole subject of radiation would probably fall under this head. Why should we expect the study of fluorescence spectra to offer more promise than the study of flame or arc spectra? The question becomes more pertinent when we remember that the spectra studied by Wood are as rich in lines and as complicated as arc spectra, while the experimental difficulties are much greater. Again, the resonance spectra and the uranyl spectra resemble closely the band spectra of ordinary spectroscopy; which, with their thousands of closely crowded lines, form a maze of such complexity that only a few spectroscopists have cared to attack them.

The strong argument in favor of luminescence appears to me to lie in the fact that in photoluminescence we have the only case, so far as I know, where the mode of excitation is definite and subject to control. Excitation by kathode rays probably comes next in order of simplicity. In a way it seems absurd to use the word simple in referring to either of these modes of excitation. But if we try to form a picture of the complex conditions that must exist in a flame, or arc, or spark, and compare such cases with the luminescence produced by monochromatic light or by kathode rays of constant and known velocity, it is like comparing the howling of a mob with the sound of a tuning fork. With sufficient patience we might find out how a piano is made by listening to the sounds produced by a crowd of unruly children pounding on the keys. But we

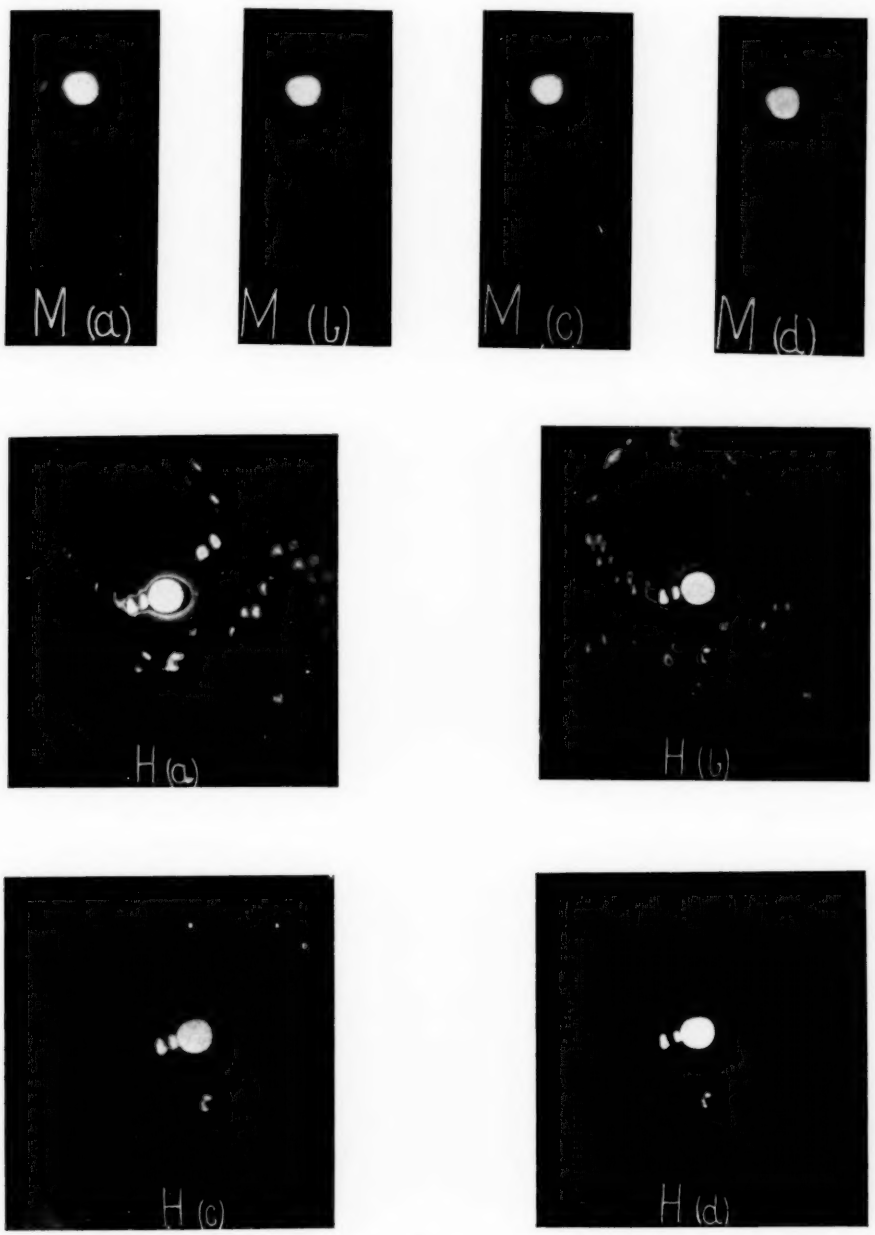

Fig. 2.

would have infinitely better chance of success if we could press one key at a time and observe the result. In the study of photo-luminescence this can be done. In fact it is exactly what Wood *has* done.

In other words, in the case of photoluminescence we can control the excitation. We can determine relations between emission and absorption, and are in a position to tell which of these relations are real and which accidental. It is not merely that we have two methods of attacking the problem of the mechanism of emission and absorption, instead of one; it means a great deal more than that. We can observe the effects produced by the mechanism; or we can determine what agencies cause the mechanism to operate; but, what is more important still, we can correlate these observations and determine what effect is produced by a given stimulus.

The spectra of photoluminescence, complex as they often are, are the simplest spectra that are known. Even Balmer's series loses its appearance of simplicity if we compare it with the constant interval series of the uranyl salts. It may perhaps be urged that the high frequency X-ray spectra possess greater simplicity. Possibly this is true. But the evidence of the most recent work does not support such a view; for as the methods of observation are improved there is every indication that the structure of these spectra is far more complex than was at first suspected. A recent photograph published by Seeman showing a part of the high frequency spectrum of platinum might well be taken for the photograph of an arc spectrum. The history of ordinary spectroscopy seems to be repeating itself. Just as we thought until quite recently that an X-ray spectrum contained only the K and L lines, so there was a time when it was thought that the sodium spectrum consisted of the D line only.

The study of ordinary luminescence cannot, however, take the place of the study of high frequency spectra as a means of determining atomic structure. There is every reason for believing that the X-ray spectra come from the nucleus of the atom; while, as Stark has pointed out, there are strong reasons for thinking that luminescence spectra originate in the vibrations of the valency electrons. In the study of luminescence we attack the outer defenses of the atom; by the aid of the high frequency spectra we attack the citadel. Our problem will not be solved until both are won.

It is interesting to note, however, that in the high frequency spectra themselves we have phenomena that are highly suggestive of luminescence. The characteristic X-rays have sometimes been called "fluorescent X-rays," in recognition of an analogy that is by no means superficial. Characteristic secondary rays are produced only by X-rays of wave-length shorter than that of the secondary rays emitted. Here we have the analogue of Stokes' law. For wave-lengths just a little shorter than that of one of its own characteristic rays a substance shows abnormally great absorption. In other words there is an absorption band immediately adjacent to the emission band on the short wave side. We have here exactly the same relation between absorption and emission that holds in practically all cases of fluorescence. Using data kindly furnished by Dr. Duane I have plotted these absorption bands for several ele-

ments and have obtained curves that have the same form as those observed in such substances as eosin and resorufin with ordinary light. Except that the wave-length scale is a thousand times smaller, the phenomena of fluorescence certainly appear to be duplicated in the high frequency spectra in every detail. It would appear, therefore, that the arguments in favor of the study of luminescence spectra will apply equally well to the case of X-ray emission.

In this brief presentation I have not had time to refer to many important phases of my subject. For example, the connection between luminescence and chemical action produced by light; the relation between luminescence and the photo-electric effect; the use of fluorescent dyes as sensitizers for photographic plates; the development of an E.M.F. by the action of light on cells with fluorescent electrolytes; and many other topics whose study is of interest both as an end in itself and as a means of attacking the general problem. My chief object will have been attained if I succeed in arousing interest on the part of some of my hearers in a subject which, in my opinion, has not received the attention that it deserves.

THE LAW OF FALL OF A DROPLET THROUGH HYDROGEN.[1]

BY R. A. MILLIKAN, W. H. BARBER, AND G. ISHIDA.

THIS paper presents the results of experiments made by the oil drop method on the law of motion of a spherical drop through hydrogen. The constant A in the correction term to Stokes Law as developed by one of the authors is not found to have quite the same value in hydrogen as in air. This means that in different gases the coefficient of slip is not one and the same function of the mean free path as Kundt and Warburg supposed it to be, and this in turn means that Knudsen's conclusion that the molecules of a gas suffer "diffuse reflection" or "re-emission" from a surface upon which they impinge is not in general tenable. Up to $(l/a) = .4$ the law of motion of an oil droplet through hydrogen is found to be given by

$$X = 6\pi\eta a v \left(1 + A\frac{l}{a}\right)^{-1},$$

in which A has the value .820 and l is determined from the Boltzmann formula $\eta = .350\ \rho\bar{c}l$. The same type of formula seems to hold generally up to $l/a =$ about .4, but A for air and oil is now found to be .845 while for air and shellac it is 1.06.

These differences are interpreted as due to differences in the law of rebound of different molecules from different sorts of surfaces.

UNIVERSITY OF CHICAGO.

[1] Abstract of a paper presented at the Chicago Meeting of the Physical Society, November 28, 1914.

NOTES ON THE ATOMIC NUCLEI.[1]

BY WILLIAM DUANE.

THE work of Sir Ernest Rutherford and his students on the scattering of α-particles has added great interest to the hypothesis according to which an atom consists of a positively charged nucleus surrounded by negative electrons. The data obtained from experiments on the scattering determine upper limits for the radii of the nuclei (supposed spherical), the limit for gold being 3×10^{-12} cm.

In order to account for the α- and β-rays, which are supposed to come from the nuclei of the radio-active atoms, and also for the relations between the chemical properties of successive radio-active elements, we assume that in general a nucleus consists of positive and negative electrons with an excess of positive charges.

A difficulty arises here. How can a lot of positive electrons remain packed so closely together? They ought to fly apart under their mutual repulsive forces, for the electrostatic forces, varying as the inverse square of the distance, cannot hold them in stable equilibrium.

It is not necessary to go beyond the classical electro-dynamics to find forces of sufficient magnitude to overcome the electrostatic repulsions. A simple calculation will show that, if two nuclei have magnetic moments equal to that attributed to the iron atom, their magnetic attraction will overcome their electrostatic repulsion, provided that the distance between them is of nuclear magnitude.

Let us assume that two iron nuclei, each having the charge E and the magnetic moment M, are placed at the distance r apart, with unlike poles pointing toward each other. The electrostatic repulsion between them is E^2/r^2 and the magnetic attraction, $6M^2/r^4$, if r is large compared with their linear dimensions. The charge E on the iron nucleus equals $26 \times 4.77 \times 10^{-10}$. In calculating the magnetic moment M of the iron atom we may take the maximum value of the magnetization in iron obtained by B. O. Peirce,[2] namely 1796. Dividing this by the number of atoms in a cubic centimeter of iron, 8.612×10^{22}, we get $M = 2.086 \times 10^{-20}$. If r_0 is the value of r for which the electrostatic and magnetic forces are equal to each other,

$$\frac{E^2}{r_0^2} = \frac{6M^2}{r_0^4},$$

and putting in numerical values,

$$r_0 = 4{,}078 \times 10^{-12},$$

a quantity of nuclear magnitude, but somewhat greater than the radius of a gold nucleus.

[1] Abstract of a paper presented at the New York Meeting of the Physical Society, February 27, 1915.

[2] Proc. of the American Academy of Arts and Sciences, June, 1913.

If the distance between the nuclei is less than r_0 they are held together, and if this distance exceeds r_0, they fly apart.

This suggests an interesting theory of the mechanism of α-radiation. Let us suppose that, owing to internal agitation, a portion of the nucleus of a radioactive atom gets thrown out by chance just beyond the point where the magnetic force can balance the electrostatic. This portion of the nucleus will then fly off just as an α-particle does.

We can estimate its final velocity as follows: Let E and E' be the charges on what is left of the nucleus and on the α-particle respectively, M and M' their magnetic moments and m and m' their masses respectively. If r_0 is the distance between them when the magnetic and electrostatic forces balance, and if the motion is along their common axis, the total work done after the particle passes this limit is

$$W = \int_{r_0}^{\infty} \left(\frac{EE'}{r^2} - \frac{6MM'}{r^4} \right) dr = \frac{EE'}{r_0} - \frac{2MM'}{r_0^3}.$$

For $r = r_0$, $EE'/r_0^2 = 6MM'/r_0^4$, and hence

$$W = \frac{2}{3} \frac{(EE')^{\frac{3}{2}}}{(6MM')^{\frac{1}{2}}}.$$

Since the kinetic energy divides itself between the two moving parts in the inverse ratio of their masses, we have for the final velocity v of the α-particle

$$v^2 = \frac{4}{3} \frac{(EE')^{\frac{3}{2}}}{(6MM')^{\frac{1}{2}}} \frac{m}{(m + m')m'}.$$

The question now arises: what values must be assigned to the magnetic moments? It is natural to suppose that the magnetic moments of the nuclei are due to the magnetic moments of the positive electrons composing them. If so, the maximum value the magnetic moment of a nucleus can have (namely when all the positive poles of the electrons are turned in the same direction), should be approximately proportional to the atomic weight of the atom, and we may calculate from this the minimum value that v can have. The smallest α-ray velocity known is that of the α-particle from Uranium I. The atomic number of this element being 92, we have $E = 90 \times 4.77 \times 10^{-10}$, $E' = 2 \times 4.77 \times 10^{-10}$, $m = 234 \times 1.662 \times 10^{-24}$, $m' = 4 \times 1.662 \times 10^{-24}$, and from the magnetic moment of the iron nucleus

$$M = \frac{2.086 \times 10^{-20} \times 234}{55.47}, \quad \text{and} \quad M' = \frac{2.086 \times 10^{-20} \times 4}{55.47}.$$

Putting these in the formula the minimum value of v becomes

$$v = 1.36 \times 10^9.$$

The most recent measurements of α-ray velocities are those of Sir Ernest Rutherford and Mr. Robinson,[1] who give for the velocity of the α-particle from Uranium I the value 1.37×10^9, in exceeding close agreement with the calculated minimum value.

[1] Phil. Mag., Oct., 1914.

The other 19 α-ray velocities range up to 2.06×10^9. These can be explained by giving proper values to M supposing that a few of the electrons are reversed and perhaps by assuming that the α-particle is projected in some direction other than along the common magnetic axis, in which case the 6 in the formula becomes smaller.

Doubtless the problem is more complicated than this elementary calculation presupposes. Further a single fact does not prove a theory. On the other hand the fact that we can calculate from magnetic data α-rays velocities which differ from the results of measurement by less than the experimental errors, does appear to have a certain significance, especially when taken in connection with certain other facts, that I hope to present to the Society at some future time.

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X-RAYS PRODUCED BY SLOW-MOVING CATHODE RAYS.[1]

BY ELIZABETH R. LAIRD.

IN these experiments cathode rays from a Wehnelt cathode fall on an anticathode. The Röntgen rays so produced pass through a well shielded window into a measuring vessel, where their presence is indicated either by the charging of a metal plate in high vacuum, or by the ionization produced when the pressure there is a few millimeters. The window is covered with an airtight celluloid film. The variation in the intensity of the radiation as measured by the photo-electric effect is shown in the curve Fig. 1. The sensitiveness of the electrometer was 2.5×10^{-15} ampere per scale division per minute. An effect was not obtained with a primary P.D. less than 200 volts. The same was true when the sensitiveness was increased by the use of the ionization method, although at 550 volts the current was increased more than a hundred times. Experiments were made with other windows. Effects obtained when the window was not quite airtight were shown to be false, in one case light from the Schumann region falsified the results. Some measurements were made on the absorption of these different substances. The celluloid films used transmitted from 40 per cent. to 70 per cent. of the radiation. The absorption in them remained roughly the same when the primary potential was varied from 300 to 1,300 volts.

Aluminium, copper, platinum, and quartz used as anticathodes gave practically the same intensity of radiation, a smaller amount was obtained from the gas alone, *i. e.*, with the anticathode displaced.

Experiments were made to measure the velocity of the secondary electrons. The results would show that with a primary voltage of 550 some electrons are present with velocities corresponding to 100 volts or more. The difficulty of avoiding secondary effects from the walls or window of the chamber has not been entirely overcome, the correction for this would be expected to make the velocities higher.

[1] Abstract of a paper presented at the Philadelphia meeting of the Physical Society, December 28–31, 1914.

Experiments were also made with another form of apparatus to test the polarization of the radiation. Only a slight amount of polarization was found.

The results with cathode ray velocities less than 200 volts do not agree with those of Dember and of Whiddington. The properties of the radiation as far as observed with the primary potential in the neighborhood of 550 volts are those of the Entladungsstrahlen from the spark at atmospheric pressure.

These experiments and the following ones were made while the writer was holder of the Sarah Berliner Research fellowship for women.

MT. HOLYOKE COLLEGE.

X-RAYS FROM THE ELECTRICAL DISCHARGE.[1]

BY ELIZABETH R. LAIRD.

IT has been found that the rays from the discharge in air at a pressure of 6 mm., previously known as Entladungsstrahlen at diminished pressure, cause a secondary radiation of electrons when falling on a metal plate in a high vacuum, and that the velocity of at least a portion of these electrons measured by an retarding field corresponds to 3,500 volts. The variation with pressure of the ionization produced between parallel plates leads also to the inference of a secondary radiation which is inappreciable after travelling a distance 0.017 cm. in air. The corresponding mass coefficient of absorption in aluminium was found to be approximately 590. These data are of the order of those obtained with X-rays of K type from calcium or L type from silver. These magnitudes show that one should not expect these more penetrating Entladungsstrahlen from a steady discharge at this pressure.

MT. HOLYOKE COLLEGE.

AN AGGLOMERATION THEORY OF THE VARIATION OF THE SPECIFIC HEAT OF SOLIDS WITH TEMPERATURE.[1]

BY ARTHUR H. COMPTON.

THIS work is based on the assumption that a degree of freedom of an atom in a solid cannot possess less than a certain critical amount of thermal energy. If its total energy falls below this value, the degree of freedom becomes "agglomerated," and remains in this condition until it again receives energy greater than the critical value.

The probability that a degree on freedom shall remain "unagglomerated" is found to be,

$$P = e^{-\epsilon/2RT} = e^{-\tau/T} \qquad (\tau = \epsilon/2R),$$

where ϵ is the assumed critical energy. The ratio of the specific heat at the relative temperature T/τ to its value at infinite temperature is then found to be,

$$C_v/C_\infty = e^{-\tau/T}(\tau/T + 1).$$

[1] Abstract of a paper presented at the New York meeting of the Physical Society, February 27, 1915.

This expression for the variation of the specific heat with temperature agrees very well with the experimental data, apparently better than the formulæ of Einstein and Debye which are based on the quantum hypothesis.

PRINCETON UNIVERSITY.

A NEW DEVICE FOR RECTIFYING HIGH TENSION ALTERNATING CURRENTS.[1]

By SAUL DUSHMAN.

THE action of the rectifier (kenotron) depends upon the emission of pure electron currents in extremely high vacua from an incandescent metal, when the latter is made cathode. Different types of kenotrons have been devised, such as a "headlight" tungsten filament placed inside a molybdenum cap, or a molybdenum cylinder with the tungsten filament placed along its axis. The current carrying capacity of the kenotron depends only upon the area and temperature of the filament (Richardson equation for electron emission), while the minimum voltage drop (V) depends upon the area, shape, and distance apart of the electrodes, and increases with the current actually rectified (i) according to an equation of the form

$$i = k \cdot V^{\frac{3}{2}}$$

(Langmuir's "space charge" equation). When i is measured in milliamperes, the magnitude of k varies in usual cases from 5×10^{-3}, for kenotrons suitable for 100,000 volts D.C. to 250×10^{-3} for kenotrons designed for 10,000 volts D.C.

Owing, however, to the fact that the filament temperature limits the maximum current which the kenotron can rectify, it is possible for the voltage over the latter to exceed the value given by the above equation, as the rectifier takes the difference between the maximum voltage available and that consumed in the load. Care should therefore be taken in using the kenotron to avoid short-circuits of the load, or some form of protective device should be used.

The actual energy losses in the kenotron may be reduced to less than two per cent. of the energy rectified.

Currents as high as 1,500 milliamperes may be rectified, but it is much more convenient to design the kenotrons so that each unit controls about 10 kw. As two or more kenotrons can be operated in parallel, this presents no limitation to their use. An arrangement of two or four kenotrons with a transformer and condensers will give direct current which can be made as free from pulsation as desired.

A detailed article dealing with this subject will be found in the General Electric Review for March, 1915.

RESEARCH LABORATORY,
GENERAL ELECTRIC CO.,
SCHENECTADY, N. Y.

[1] Abstract of a paper presented at the New York meeting of the Physical Society, February 27, 1915.

THERMAL CAPACITY OF TUNGSTEN AT INCANDESCENT TEMPERATURES, AND AN APPARENT LAG OF RADIATION INTENSITY WITH RESPECT TO TEMPERATURE.[1]

BY A. G. WORTHING.

THE characteristic equation for a uniform filament mounted in an evacuated bulb, heating or cooling from one temperature to another due to a change in the heating current is

$$IV = f(T) + cm\frac{dT}{dt}$$

on the supposition that it passes through a succession of steady states. I, V and T represent the instantaneous values of current, potential drop, and temperature, m the mass of the filament, c the thermal capacity of the substance of the filament and t time. The three terms represent respectively the rate of heat production in the filament, the rate of radiation of energy from the filament, and the rate of change in the heat energy of the filament. The instantaneous values of I and V were measured on a potentiometer with the aid of a pendulum device. The values assumed for $f(T)$ were the wattages under steady current conditions corresponding to the resistances given by V and I. In some cases the cooling effects of the junctions were eliminated by taking the differences obtained using two filaments differing only in length when heated by the same current. In all cases it was found that the c–T relation obtained when the filament was heated from some low temperature to some higher temperature, was different from that obtained when it was cooled from the higher temperature to the initial low temperature. The difference was always consistent with the assumption that while the temperature is changing, the radiation intensity lags with respect to the temperature as determined by resistance measurements. Assuming the mean of such c–T relations to be the desired relation, and the temperature scale that determined by Mendenhall and Forsythe the following values have been obtained.

T in °K	c in $\frac{\text{cal.}}{\text{gr.} \times \text{deg.}}$
1,600	.042
1,800	.044
2,000	.047
2,200	.050

Results thus obtained are in good agreement with results obtained by a slight modification of Corbino's method in which the same filaments were used.

NELA RESEARCH LABORATORY,
CLEVELAND.

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, November 27–28, 1914.

On the Reflecting Power of a Certain Selenium Crystal.[1]

By L. P. Sieg and F. C. Brown.

THE reflecting power, and other optical constants of metallic and amorphous selenium mirrors have been determined several times. The latest work has been done by Foersterling and Fréedericksz.[2] While working with large selenium crystals the question arose as to whether or not the optical properties of these crystals were the same as for the metallic modification or the amorphous varieties, or differed with the different types of crystals. Only a preliminary study was made, but work is being done in this laboratory toward obtaining a complete study of the optical properties. The reflecting power of the selenium as used by Foersterling and Fréedericksz was practically constant from wave-length 0.289 μ to 0.740 μ, varying from 0.36 to 0.25 at the longer wave-length. The present work indicated with certainty that the reflecting power for a lamellar crystal, from 0.37 μ to 0.80 μ was practically constant. Exactly what the coefficient is, has not been determined with any great accuracy, as the principal concern was to discover any variations, if any, in the reflecting power. This information was of great importance in connection with work on the light-sensibility curves.

State University of Iowa.

The Arc in a Longitudinal Magnetic Field.[1]

By R. F. Earhart.

SOME experiments were made with a carbon arc, using both cored and solid carbons, when the arc was placed in a uniform magnetic field. The lines of magnetic force were parallel to the axis of the carbon electrodes. The effect of establishing fields varying up to 2,000 c.g.s. units was to reduce the current and to increase the P.D. between the terminals. The behavior was studied by determining the characteristic curves for the arcs with fields of different strength. The characteristic curve produced when the field is established is similar to one which would be obtained by lengthening the arc. It was noticed that the heat developed at the positive carbon was increased when the field was established. In such case an increased length of carbon became red hot. This indicated that the anode fall in potential had been increased. Such was found to be the case when an exploring electrode was introduced. The cathode drop was increased but the anode drop had a greater relative increase than the cathode drop. The instability of the arc is increased with the application of the magnetic field. Unequal consumption of the carbon tips causes considerable difficulty.

Ohio State University.

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, November 27–28, 1914.

[2] Ann. d. Phys., 43, p. 1227, 1914.

TRANSMISSION OF SOUND THROUGH FABRICS.[1]

BY F. R. WATSON.

THE transmitting power for sound of different materials was determined by allowing sound to pass through the material in question and noting how much the intensity was diminished as compared with the unhindered sound when the material was removed. A whistle blown by a constant air pressure and backed by a parabolic reflector directed the sound through an open doorway into an adjacent room where its intensity was measured by the deflection of a Rayleigh resonator. One, two and three layers of material were then placed successively over the doorway and the intensities measured each time. The preliminary results indicate that the intensity falls off in a decreasing geometrical progression as the thickness of material increases in an arithmetical progression.

UNIVERSITY OF ILLINOIS.

A DIFFERENTIAL DYNAMIC METHOD FOR THE ACCURATE DETERMINATION OF THE VAPOR PRESSURE LOWERING OF SOLUTIONS.[1]

BY E. W. WASHBURN.

THE chief sources of error in the determination of vapor pressure lowering of solutions by the gas-saturation method as heretofore carried out are (1) the difficulty in measuring with sufficient accuracy the large volume of gas aspirated; and (2) the error due to temperature variation in successive experiments. Both of these sources of error can be practically entirely eliminated by placing the saturation trains, containing the pure solvent and the solution respectively, close beside each other in a well stirred constant temperature bath and aspirating the gas through both saturation trains in succession, the solvent vapor being removed from the gas stream by suitable absorbers placed immediately after the last saturator in each train. Under these conditions it is not necessary to know the volume of the gas aspirated, which can, therefore, be made as large as desired. Moreover, temperature variations even as large as 0.1 degree in a well stirred bath will not produce an appreciable error since both solution and solvent are affected nearly alike.

With this method and with solution in the first saturator and pure solvent in the second the relative vapor pressure lowering is given by the following expression:

$$\frac{p_0 - p}{p_0} = \frac{D_m(B - P_1 - p_0) - m_0 D_p}{m_0(B - P_2) - D_m p_0}.$$

D_m is the difference in the amounts of solvent vapor taken up by the two absorbers respectively and this difference is directly determined by placing the

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, November 27–28, 1914.

absorbers (which are identical in form) on opposite pans of a balance. m_0 is the mass of solvent evaporated from the saturator containing the solvent, as determined by the increase in mass of the second absorber. B is the barometric pressure. p_0 is the (approximate) value of the vapor pressure of the pure solvent. P_2 is the difference between the barometric pressure and the pressure at which the aspirated gas leaves the second saturator while $D_p(= P_2 - P_1)$ is the difference in the pressures at which the aspirated gas leaves the two saturators respectively. Both P_2 and D_p which are very small are directly and accurately measured by means of two small inclined differential water manometers which are connected at the proper points in the system.

The precision of the result is wholly determined by the precision with which D_m is measured since all of the other quantities can be easily measured with 10 or 100 times the precision necessary. D_m increases with the concentration of the solution employed and with the quantity of air aspirated.

This method has been tested in this laboratory by Mr. H. B. Gordon and by Mr. E. O. Heuse. With molal aqueous solutions at 25° they find that an accuracy of about 0.25 per cent. is attainable in the value of $\frac{p_0 - p}{p_0}$ by this method.

LABORATORY OF PHYSICAL CHEMISTRY,
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NEW BOOKS.

Analytical Mechanics. By HAROUTUNE M. DADOURIAN. New York: D. Van Nostrand Company, 1913. Pp. xii+353.

This is a text-book of a grade intermediate between a part on mechanics in a college text-book on general physics and a treatise intended for graduate students. Apart from the numerous examples that are admirably worked out in the text, the excellent press-work, and the well-designed cuts, the most marked feature of the book (accentuated by the author) is the adoption of a modified form of Newton's third law of motion as the single fundamental feature in the treatment.

The author first quotes Newton's law in the form, "To every action there is an equal and opposite reaction, or the mutual actions of *two bodies* are always equal and oppositely directed," and then modifies the second clause to read, "or the sum of all the actions to which *a body* or a part of a body is subject at any instant vanishes," or $\Sigma A = 0$. The italics (ours) indicate the modification. It is arrived at by associating four concepts with the term "action" —force, torque, linear kinetic reaction, and angular kinetic reaction. These are introduced in succession as the development requires. Force, defined as "a vector the magnitude of which represents the action of one body on another" and torque, "the vector magnitude which represents the angular action of one body on another," suffice for statics. Linear kinetic reaction is described as the resistance which a body offers to a force which accelerates it. The mass of a body is then defined as "a constant scalar magnitude which equals the quotient of the magnitude of the kinetic reaction of the body by the magnitude of its acceleration" and the measure of kinetic reaction is then defined as $-mf$ (acceleration). (The logical order of the ideas in this process is not quite obvious.) Thus the general law becomes for a single body $\Sigma(A_l + A_a) = 0$. "Since the two types of action are independent of each other, the sum of each type must vanish." $\Sigma A_l = 0$ (linear), $\Sigma A_a = 0$ (angular). (But should they be represented as additive, being of different dimensions?) This system evidently leads to great simplicity in the formula for the fundamental principle. But the multiple-valued concept "action," in its protean adaptibility, seems likely to be a source of some vagueness in the mind of a student. "Kinetic reaction" is d'Alembert's "reversed effective force," conceived, however, as an entity, not as a convenient fiction, or it is the equivalent of the long banished "force of inertia." It does not seem to have the intuitional element desirable for use in a fundamental principle; this is probably the element that has given Newton's somewhat illogical arrangement of his laws of motion their persistent

vitality. Will not a beginner be troubled by finding that in the case of two connected bodies there are are four actions, a force and a kinetic reaction for each? The author seems himself to have difficulties in finding the right word in referring to kinetic reaction. He cannot of course speak of it as being exerted on or by a body, but refers to it as something which "manifests itself," which a body "displays" or which "appears" when the body is accelerated. Students are likely to have still greater difficulties in this respect. Language and thought are inseparable, and ideas that are not readily clothed in words are indistinct. Others (*e. g.*, Love) have, in fact, used kinetic reaction as meaning $+ mf$. Mass, from its definition, will share in whatever haziness there is in kinetic reaction; likewise kinetic energy, defined by work done against kinetic reaction (two minus signs being required in the integration p. 187). The "normal kinetic reaction" of a particle revolving in a circle recalls "centrifugal force" when this was regarded as a force driving the body from the center. Yet the author's attempt at a new formulation of axioms is interesting. But, on the whole, while we may not be prepared to follow the suggestions of Tait and Kirchhoff and banish force, replacing it by a time rate of transference of momentum or a space rate of transference of energy, it seems doubtful whether the way out of the difficulties is to be found in the introduction of new variants of the force concept.

But the above criticism of one aspect of the book (on which, however, the author lays stress) does not apply to its many admirable features. The author has especially done well in treating under the head of Dynamics many problems which are usually discussed under Kinematics, thus emphasizing the physical aspect of the subject.

A. W. D.

The Theory of Heat Radiation. By DR. MAX PLANCK. Authorized translation from the 2d German Edition, by DR. MORTON MAZIUS. Philadelphia: P. Blakiston's Son and Co., 1914. Pp. ix+225. Price, $2.00.

As the translator remarks, most of those directly interested in this book can read it in the original. But the difficulties inherent in Planck's treatment are such that probably many of these will welcome the opportunity of studying the subject without having their attention at all diverted by linguistic troubles. There will also, let us hope, be many less directly interested readers who would never dip into the book at all if this translation had not removed one of the difficulties. The translation is entirely adequate as to clearness, and the translator has added two useful appendices, one dealing with Stirling's formula, and the other a bibliography of the more important papers, reports, etc., dealing with the quantum theory in its general aspects. Some of these references are accompanied with brief abstracts. It would be very valuable if this bibliography could be extended and the abstracts amplified in a future reprint.

C. E. M.

Tensoren und Dyaden im Dreidimensionalen Raum. Ein Lehrbuch von E. BUDDE. Braunschweig: Vieweg and Sohn, 1914. Pp. xii+248. Price, Mk. 6.

A knowledge of vector analysis becomes daily of more and more importance to the physicist. This is not a book on vector analysis, but on that part of it which has to do with the mutual relations of pairs of vectors such that the components of either are linear components of those of the other. According to the terminology here adapted, if the matrix of nine coefficients is symmetrical we have a tensor, if not a diatensor. The geometry of these various relations is very thoroughly explained, together with the applications to linear deformations, and the applications to the differential geometry of strains in general. It seems to the reviewer as if the physicist might get on with far less extended knowledge than this book presents, but there is no doubt that it is very well presented. A. G. W.

General Chemistry. Part I. Principles and Applications. By LYMAN C. NEWELL. Boston: D. C. Heath and Co., 1914. Pp. vi+174. Price $1.25.

This is one of the good books now available for those who wish to teach or to study chemistry in the high schools. In the preface the author states that the one point kept in mind during the preparation of the book was that "principles and applications must go hand in hand. Principles are the foundations upon which applications rest. To teach either one exclusively is hazardous, for when separated one is as barren as the other is superficial." It may be wondered if in high-school chemistry a greater use of the concept of the molar volume of gases than is made in the usual text-book might not be a valuable aid in teaching the subject. It might be possible too, to so develop the subject of atomic weights as to show the student that these weights may be obtained without the use of Dalton's atomic theory.

A feature of this book which should increase the interest of the students is that it contains a set of about twenty-five experiments on the subject of foods.

W. D. H.

The Sun. By R. A. SAMPSON. New York: G. P. Putnam's Sons, 1914. Pp. viii–141.

An unusually good example of popular scientific exposition. In a small space it treats practically all the phases of solar investigation. The treatment is sufficiently popular to make it interesting reading for any one of ordinary information, and yet its scrupulous accuracy should give it a place in the library of the scientific observer. The author has evidently used great care in giving due weight to the most recent investigations, so that it is probable that if the work of Grotrian and Runge on the "So-called Cyanogen Bands" had been published before the book was in print he would have made less positive his assertion (p. 125) that cyanogen has been found in the sun.

L. B. T.

Cours D'Electricite Theorique. By J. B. POMEY. Paris: Gauthier-Villars, 1914. Pp. viii–396. Price 13 fr.

This course of lectures given to the students of the "École Professionnelle Supérieure des Postes et Télégraphes" should be interesting reading for any teacher of theoretical electricity, because of its wide difference from the English and German treatments which are more familiar in America. It suggests that the preliminary training of the French technical students must be very different from that of the corresponding American students and the usefulness of the book in the hands of American students must therefore be limited. As an illustration of the difference, Green's Theorem is nowhere mentioned, its place being taken by a number of special theorems,—the Theorem of Vaschy, the Functional Equation of Robin, the Formula of Ostrogradski, etc. Under the last named we recognize what we customarily call Gauss' Theorem.

It is hard to understand why the sixty odd pages on vector notation should be postponed till Chap. IV., when the notation would have been as useful in the three preceding chapters as in the following four. This chapter adds another to the already numerous hybrids between the Hamiltonian and Continental vector notations.

L. B. T.

Scientific Papers. By J. Y. BUCHANAN. Vol. I. Cambridge, The University Press, 1913. Pp. xii+54.

This book is simply a collection of fifteen oceanographical papers reprinted exactly as they were originally published elsewhere. They deal with observations made on the Challenger expedition and also on the S.S. *Buccaneer.* They relate to the distribution of salt, of temperature, and of absorbed gases in the ocean, to the exploration of ocean shoals and ocean basins, and to general methods of attacking problems of this character.

R. A. M.

The Spectroscopy of the Extreme Ultra-Violet. By THEODORE LYMAN. New York, Longmans, Green and Co., 1914. Pp. v+135. Price $1.50 net.

The spectral limits were first set by the human vision. Next came the extension of heat rays toward the red end of the spectrum and of actinic rays toward the violet. In the violet the limit was set by the absorption of the apparatus; and, as Schumann showed, by the absorption of the gelatine of the photographic plates and the gases through which the light was compelled to pass.

Lyman has improved upon the Schumann's apparatus by employing a grating vacuum spectrograph. He also very cleverly introduced a double slit. Through one slit he could photograph to extreme ultra-violet. Through the other slit he could obtain known lines. With the two sets of lines in juxtaposition the wave-lengths of unknown lines could be accurately measured. By farther reducing absorption, Lyman has succeeded in doubling (when

measured in wave frequency) the limits of the Schumann region. The opacity of oxygen for these short radiations is particularly noteworthy.

This book is a brief (too brief) account of the work which has been accomplished in the extreme ultra-violet, known as the Schumann region. We need now, more particularly, to increase our information upon that part of the spectrum between the Schumann region and the limits of the sun's spectra.

B. E. M.

Text Book on Wireless Telegraphy. By RUPERT STANLEY. New York, Longmans, Green and Co., 1914. Pp. xi+344. Price, $2.25 net.

This is a text-book rather than a treatise, being intended for actual class-room use. Having in mind the needs of those who intend to become wireless operators, but who have little knowledge of electrical matters, and also the needs of amateurs who are interested in wireless telegraphy but not familiar with the principles on which it is based, the author begins with several chapters on the general subject of electricity and magnetism. These are followed by a chapter on oscillatory discharges and another on electric waves. About one third of the book is taken up with such preliminary work, after which the methods and apparatus of practical wave telegraphy are discussed in a manner which, is, on the whole, extremely clear and satisfactory. The weakest point about the book is the inadequacy of the treatment of the fundamental properties of electric oscillations and waves. It is hard to see how the latter parts of the book can be really appreciated by one who depends for his knowledge of these fundamental topics upon the two short chapters which Professor Stanley devotes to them. For one who is well grounded in in the physics of electric waves and oscillations the book will be found extremely interesting and valuable.

E. M.